ISSN 0024-8266

# mnassa

monthly notes of the astronomical society of southern africa

Volume 80 Nos 5-6 June 2021

In this issue:

**Award of Overbeek Medal to Magda Streicher and Clyde Foster**

**Asteroid 2018 LA**
**(Observed in space and recovered on the ground)**

**The Eta Aquariids in 2021**

**Visit to SARAO Carnarvon**

***Cover:*** *Fragment of Asteroid 2018 LA.* For only the second time ever, the entry of a small asteroid was observed from space prior to impacting on Earth (June 2, 2018). Pieces of it were collected from the impact site. See article on p. 77.

mnassa

Vol 80 Nos 5-6 June 2021

## ASSA News: Overbeek Medal

The purpose of ASSA's Overbeek Medal is to recognise long-term, high-quality observational work by members of the amateur community, especially those having scientific merit. The award is named in honour of the late Danie Overbeek, the Guinness book of Records champion of visual variable star observations. The medal, struck in sterling silver, bears his likeness engraved on the obverse, with the recipient's name and the year of award on the reverse.

*Above: Magda Streicher and Clyde Foster show off their Overbeek Medals.*

No more than one medal can be awarded in any given year. However, due to logistical reasons pertaining to the Covid-19 pandemic, the candidates for two consecutive years were announced at the 2020 AGM, with the physical handover of both taking place at a small ceremony in Pretoria on 26 May.

**2020 Overbeek Medal – Magda Streicher**

Magda Streicher is South Africa's doyenne of deep sky observing and has been so for over 20 years. She has developed a unique way of recording her results; in an age when digital astrophotography dominates both amateur and professional observations, Magda still draws the most accurate and beautiful sketches of her observations. These, accompanied by a brief but frequently poetic description, provide a good impression of what a visual observer can expect to see. These observational records get published in MNASSA, Nightfall and several overseas journals as "Deep Sky Delights".

Her books and catalogues consolidating her observations are well known; her Astronomy Delights (published in 2012), is a beautiful miscellany of her Deep Sky Delights for which she was deservedly awarded the McIntyre award. This year she has added details of all 88 constellations that she has observed over the past many years, to her volume of Astronomy Delights, creating an incredible, massive volume of over 550 pages! Finally, her observation of Sirius B after many years of eye watering attempts, turned to tears of joy when she succeeded recently; she regards this as her crowning glory. Many amateurs have imaged it digitally, with difficulty, but very few have actually seen it. Being Magda, she spent a long time sketching what she saw and published it. Magda has observed the night sky in a way that would have made Danie Overbeek proud.

**2021 Overbeek Medal - Clyde Foster**

Clyde Foster's digital imagery of Shallow Sky objects - primarily that of the major planets and the occasional comet - has grown enormously over the past few years. His work has involved interaction with other amateurs, and a number of professional astronomers, both locally and internationally. His recent images of the planets Saturn and Jupiter, mainly the latter, where he has collaborated with the NASA's Juno mission team, have produced images with a resolution that almost challenges the laws of Physics!

He has been active member of the ASSA in promoting, and participating in, pro-am collaborations and been overseas several times to do this, where he has presented at international Conferences on Planetary imagery. His discovery of a feature on Jupiter's surface, aptly named Clyde's Spot, indicates the level to which his work has risen and been recognized. A year after its discovery, Clyde's Spot continues to evolve in complex ways, with its unexpected longevity enabling it to be actively monitored over a comparatively long duration, thereby providing clues into the atmospheric dynamics of the gas giant.

# The super-bolide of June 2, 2018 and meteorites from asteroid 2018 LA

*Tim Cooper, Comet, Asteroid and Meteor Specialist, Shallow Sky Section, Astronomical Society of Southern Africa*

**Summary**

Asteroid 2018 LA, discovered around eight hours earlier on the morning of 2018 June 2, crashed into earth's atmosphere at 16h44 UT. With a size of about 1.6 metres and travelling at 17 km/second it produced a bright fireball which disintegrated over Botswana. A number of fireball reports were submitted to the ASSA webpage, and security video footage was posted on several social media sites, including the Sterre en Planete Facebook page. These played an important role in an international investigation of the fall and the subsequent recovery of fragments from asteroid 2018 LA. After an exhaustive analysis of the meteorites, a report on the findings was published in Meteoritics and Planetary Science on April 23, 2021. The collective finds have now been classified as the Motopi Pan (MP) meteorite, which is found to be a eucrite-rich howardite, part of the howardite-eucrite-diogenite (HED) class with a likely origin at asteroid 4 Vesta. ASSA participated in this study. This article describes the timeline of events, procedures followed in order to analyse the various videos and reports in order to define the location of the strewn field for the initial search in June 2018, and the subsequent search for meteorites in October 2018. Video footage was also calibrated in order to measure the brightness of the fireball which reached absolute magnitude –23 at disintegration. Suggestions are made on how the investigation of future very bright fireball events can be improved in order to recover other potential meteorites.

**Previous bright fireball events**

There is a regular occurrence of bright fireballs over southern Africa, resulting from the entry of small asteroids potentially large enough to produce meteorites. Efforts to date to triangulate potential fall sites in southern Africa have been uncoordinated and did not directly result in the recovery of meteorites. Now, the unusual entry of a small asteroid observed in space prior to impacting over land on June 2, 2018, only the second time in recorded history, enabled ASSA to participate in a coordinated investigation (SAFC #305), which led to the recovery of 23 fragments from asteroid 2018 LA.

Since the inception of the Southern African Fireball Catalogue (SAFC) in 1992, there have been several instances of very bright fireballs with $m_v > -10$, of which at least two may be classified as super-bolides (#225 and #305). The definition of a super-bolide (see Cooper 2017a) is a fireball with absolute magnitude > –17. Recent bright events (with SAFC number) were as follows (note all times used in this report are given in UT):

2002 July 21, SAFC #116, a bright daylight fireball was seen independently by two aircraft pilots, as well as amateur astronomer Bill Hollenbach, who estimated $m_v$ about –10. The visual reports did not permit triangulation of the fall location, but the fall was witnessed in the village of Thuathe, Lesotho, resulting in the recovery of the Thuathe Meteorite. The combined mass of fragments recovered was 45.3 kg (Russell et al 2003).

2003 November 26, US Government sensors (Chamberlin 2018) detected an atmospheric explosion at 02h00 and location 22.7°, –22.9°, altitude 32.0 km, in a remote area of western Botswana and roughly 100 km north of the town of Kang, with calculated total impact energy 0.12kT. No visual reports of this fireball were ever received.

2009 November 21, SAFC #225, a very bright bolide was widely observed at around 21h00. The subsequent explosion was recorded at coordinates 29.2°, –22°, located in the Tuli Safari Area of Zimbabwe, with a calculated total impact energy of 18kT. The airburst was detected by two seismic recorders outside South Africa (Brown 2009), and allowed a tentative location of the airburst over south eastern Botswana. The author analysed fifty-six separate eye witness accounts to determine a fall site most probably in south-western Zimbabwe. Though the opportunity presented for the first time to triangulate the potential fall site from video records, insufficient useful footage was obtained to do so and the opportunity to discover freshly fallen meteorites was lost.

2013 March 12, SAFC #249, a bright daylight fireball was observed at around 10h35 from the Western Cape. The explosion registered at coordinates 17.1°, –32.7° with a calculated total impact energy of 0.1kT. Analysis by the author (Cooper 2013) of nine eye witness accounts was consistent with a location west of Cape Town, moving towards the north-west and any possible meteorites would have fallen offshore.

2017 June 15, SAFC #288, fifty independent reports were received of a very bright bolide at 04h03. Duration 8-10 seconds, with brightness probably in the range $m_v$ –12 to –15. The path was from south of Dordrecht in the Eastern Cape, crossing Fouriesburg in the Free State, and burned out in the north eastern Free State somewhere near Frankfort or Cornelia. Sounds were heard over the area of the Northern Drakensberg. No video records were obtained which could have enabled location of a possible strewn field for potential meteorites. A full report and analysis has been given by Cooper (2017b).

## Discovery, orbit and path of 2018 LA over southern Africa

The entry of asteroid 2018 LA into earth's atmosphere resulted in a super-bolide which was seen over a wide area including South Africa, Botswana and Namibia. Because this was only the second time an asteroid was spotted in space before impacting Earth, the first being asteroid 2008 TC3 over Sudan ten years earlier (Jenniskens et al. 2009), there was particular interest in finding surviving fragments on the ground. For the first time with a bright fireball event in Southern Africa, video footage was obtained and calibrated with sufficient accuracy to define a reliable strewn field location, resulting in the recovery of several meteorite fragments, now jointly classified as the Motopi Pan meteorite (Meteoritical Bulletin no.110, in preparation). A report on the international effort to recover the meteorites and study them in the laboratory, in which ASSA participated, was recently published in Meteoritics and Planetary Science (Jenniskens et al 2021).

Asteroid 2018 LA was discovered on 2018 June 2.3443 on images taken with the 1.5m reflector of the Catalina Sky Survey, a NASA funded project supported by the Near Earth Object Observation Program (NEOO) under the Planetary Defense Coordination Office (PDCO), based in Tucson, Arizona (Matson 2018, Williams 2018). As with 2008 TC3, the supporting astronomer was Richard Kowalski. Follow up observations were secured with the 1.0m reflector at Steward Observatory, Mount Lemmon. Before impact, the position of the asteroid in its orbit was so poorly known that there was only a small probability the asteroid had impacted. Possible impact solutions stretched all the way from Madagascar, over the Indian Ocean into the Pacific (Figure 1). Most possible trajectories suggested a near-miss.


*Fig 1. Composite of predicted impact locations of asteroid 2018 LA from Gray (2018) created by merging two plots from original CSS observations (right hand portion from Indonesia to Madagascar) and after ATLAS observations (left hand portion over southern Africa).*

After impact, two more observations were reported from the 0.5m Schmidt telescope of the ATLAS (Asteroid Terrestrial-impact Last Alert System) based at Mauna Loa. Based on these observations, Bill Gray (2018) and others calculated an impact area in Namibia and Botswana (Figure 1). 2018 LA would approach from the East and reach an altitude of 30km in the earth's atmosphere at about 16h48 UT, with the probability of impact estimated as 83% located over Namibia.

**First reports of the bolide from 2018 LA**

First indications that the impact was actually over Botswana came from fireball reports. Two members of the public reported seeing a bright fireball in the early evening of Saturday June 2. The first report was received just a few minutes after the visible fireball, at 16h53 from Julian Naik, who was staying at the Maropeng Hotel. Shortly afterwards at 17h04, Jacques Naudé just north of Polokwane airport also reported seeing the fireball to his north west. Both observers gave the time as 16h45 and described the fireball ending with a bright flash on the horizon. With these two reports I logged the event in the SAFC (#305) for follow-up. At 19h29 I received a link from Kos Coronaios to the first sighting report on Facebook posted by Shane Seaman, who was at Sitatunga Camp near Maun, Botswana. He did not see the fireball, but saw a very bright light which lit up the whole area. Further sighting reports followed quickly after this. At 00h29 on the morning of Sunday June 3, I was awoken by my mobile phone ringing. Half asleep and assuming it was a prank caller I ignored it and tried to get back to sleep. About ten minutes later my phone beeped to alert me to an incoming email. So by now up and awake, I walked to my study and downloaded my email. It was from meteor astronomer Dr Peter Jenniskens of the SETI Institute and NASA Ames, saying:

*An asteroid was detected in space and tracked briefly. There is a 38 percent chance it impacted. Along the potential impact path is the north of South Africa and Botswana. There now is a report of a fireball at 16:44 UT (June 2, 2018) seen from Gaborone. Can you please find out more about this event if you can?*

While I was still digesting the mail Peter phoned a second time, and in the next half hour we were able to link all the sighting reports received until then with the asteroid, then still known under the preliminary designation ZLAF9B2. By this time also the first video footage of the bolide had been posted by Barend Swanepoel, with the note ''Very bright Meteor landed close to Ottosdal North West'', and while at no time did we suspect that anything had fallen near Ottosdal, we now had the first crucial information that would enable us to determine exactly where the explosion occurred. In the next few days I would travel nearly 4500 km analysing videos and collecting eye witness reports of the event.

**Calibration of video records of the bolide**

In the days following the event, US Government satellites reported a bright flash at 28.7 km altitude over the Central Kalahari Game Reserve (CKGR) and provided a time at 16:44:12 UTC, but with unknown uncertainty intervals (Chamberlin 2018). That time and place much better defined the asteroid position in its orbit and improved the asteroid's trajectory in the atmosphere from calculations by Davide Farnocchia at JPL and by Esko Lyytinen in Finland (McDonald 2018). The location of the impact was now confirmed to be over the CKGR. However, the uncertainty of the position of that trajectory was unknown and could still be many kilometres off.

We needed to verify the US Government reported position and time, and determine the point along the track where the explosion occurred as accurately as possible. This point was of vital importance since the strewn field of any potential meteorites would be linked to this location. The bolide and explosion were captured on several videos, and are grouped in Table 1 into either those that captured the visible flight of the bolide or those that captured shadows from the terminal flash from the explosion. Both types were useful once calibrated in order to determine the time and direction of the explosion. Locations of the six videos are shown in Figure 2, and the following gives some idea of the process followed in calibrating the videos.

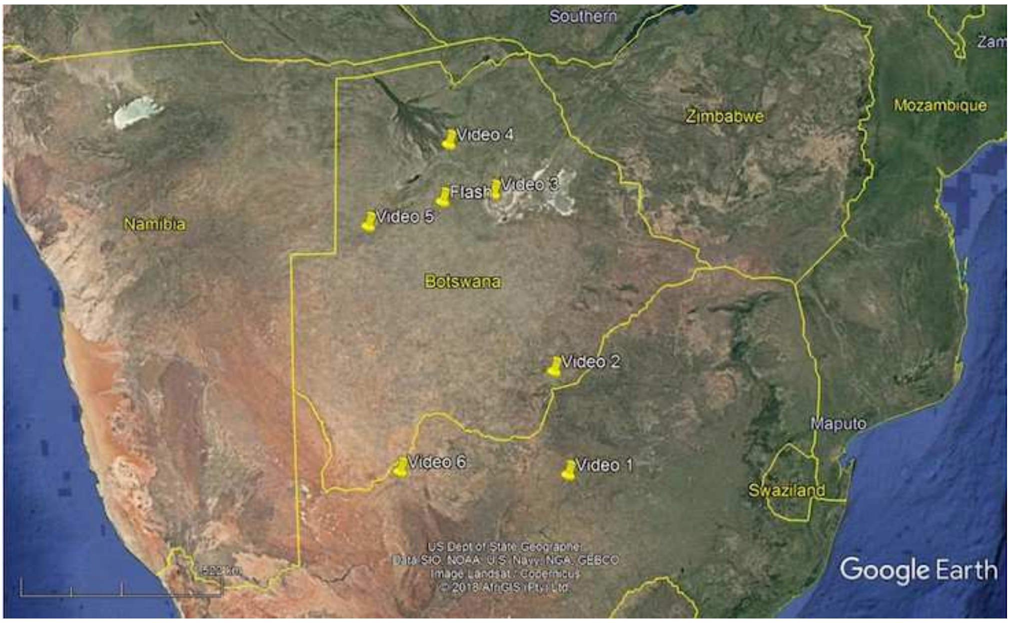


*Fig 2. Locations of video cameras listed in Table 1, and used to determine the precise location of the explosion after calibration and astrometry. (Image courtesy of Google Earth.)*

Video #1 from Ottosdal was the first to appear on the internet, having been uploaded by Barend Swanepoel. The bolide appears upper right and travels downwards towards the left, and was out of view for a short period before ending in a bright flash. The time stamp shows the time as just after 16h49. The author visited the site in order to calibrate the video footage on June 7, 2018. The first task was to calibrate the time

| | **Location** | **Bolide or shadow** | **Video calibrated by** |
|---|---|---|---|
| 1 | Ottosdal, South Africa | Bolide | Cooper |
| 2 | Gaborone, Botswana | Bolide | Cooper |
| 3 | Rakops, Botswana | Shadow | Jenniskens & Moses |
| 4 | Maun, Botswana | Shadow | Jenniskens & Moses |
| 5 | Ghanzi, Botswana | Shadow | Cooper & Moses |
| 6 | Nr Hotazel, South Africa | Bolide | Uncalibrated |

*Table 1. Locations of video footage shown in Figure 2.*

stamp, which was compared with internet time using the Time Calibrator app available for download on Android devices. The corrected time of start of passage was at 16h44m03s UT, and end of passage at 16h44m07s UT. The next task was to calibrate the images in order to determine the direction of the terminal flash. This was achieved by positioning a DSLR camera directly in front of the video camera in such a way as to ensure the same image perspective, and exposing after darkness in order to capture sufficient stars to give accurate astrometry of the image. The security camera frame grabs were then superimposed on, and aligned with the calibration image. Since the positions of stars in the calibration image could be determined accurately at the time the image was taken, the coordinates of the bolide at various points in its trajectory were determined and extrapolated to the flash position. This gave us our first indications of the entry point of 2018 LA into the atmosphere, and the exact position in its path where it disintegrated.

Video #2 was secured from a commercial property in Gaborone. The author visited the site on June 10, 2018 and calibrated the footage in the same way as described previously. Screen grabs are shown as Figure 3 and have a time stamp just after 18h42 local time (16h42 UT). The bolide enters upper right and is visible for four seconds, before disappearing behind a building, and terminates 1.7 seconds later with a very bright flash which saturates the image. The calibrated time of the flash was determined as 16h44m18s, which is several seconds later than the time determined from the Ottosdal footage. We ascribed the difference due to clock drift in the two computers over the several days between June 2 and the date of calibration, and as a result concluded the calibrated times could not be used to accurately determine the point of
explosion. The Gaborone footage was also used to determine the azimuth of the bright flash by taking calibration images with a DSLR camera and superimposing the frame grabs from the video footage on the calibration images, as shown by example in Figure
4a. This was done for several frame grabs, and Figure 4b shows the calibration image with the fireball images removed to leave points at one second intervals along its path superimposed on the calibration image. The path was then projected to the bright flash and its azimuth direction determined. This resulted in a second vector, which showed an excellent coincidence with that found from Ottosdal.


*Fig 3. Frame grabs from Gaborone video; three frames showing motion of bolide at 1 second intervals. Disruption occurred after passing below the level of a distant building.*

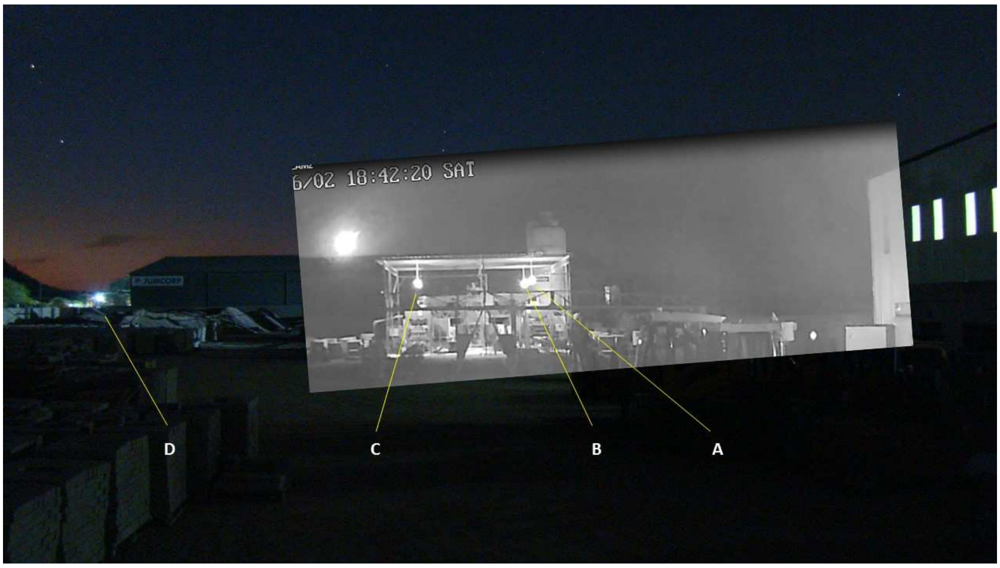


*Fig 4a. Calibration image for Gaborone taken by the author on June 10, 2018, showing superimposition of frame grab with bolide shortly before it disappeared behind a nearby building. Letters denote lamps, the brightness of which were calibrated to allow photometry of the bolide (Figure 8 in Jenniskens et al., 2021).*

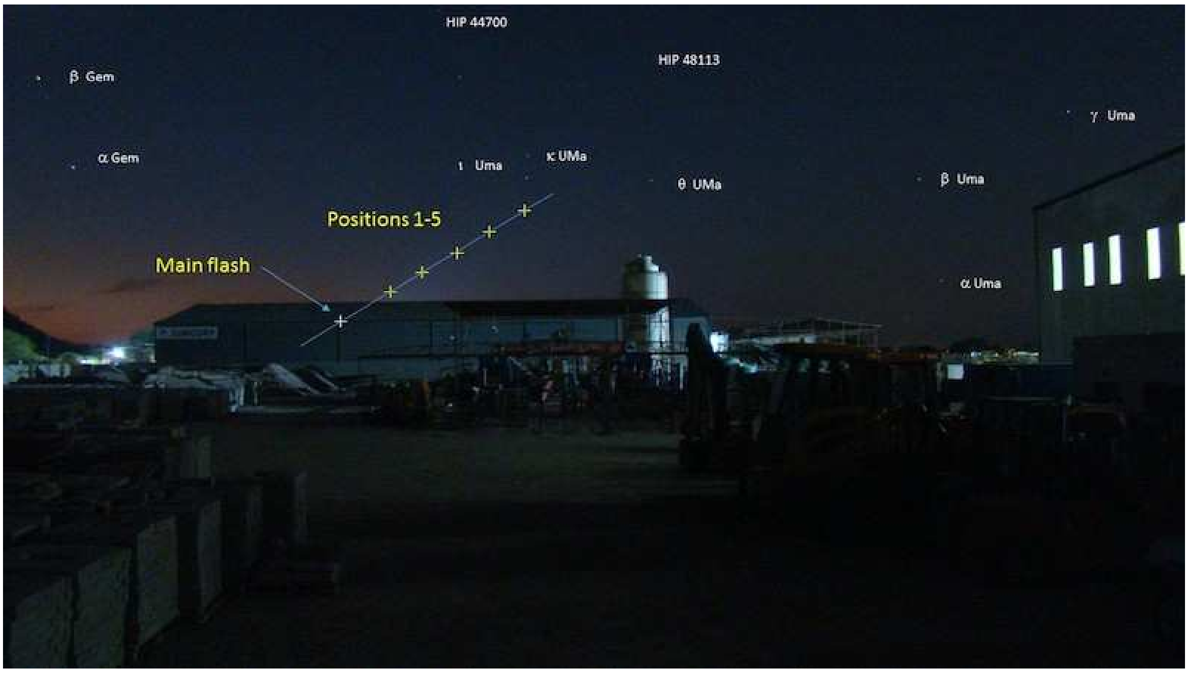


*Fig 4b. Calibration image for Gaborone taken by the author on June 10, 2018, after superimposing frame grabs, marking the positions of the bolide, and then removing the frame grabs. Coordinates were measured using stars labelled for astrometry. Coordinates along the path of the bolide were measured in 1 second intervals and the path was projected to the bright flash to determine the location of the disruption.*

From Gaborone, the author proceeded along the A2/A3 highway up the western side of Botswana towards Maun. Stopping in the town of Ghanzi he located video #5 from a petrol garage security camera, which did not capture the actual bolide, but did capture its reflection on the roof of the dark vehicle in the image in Figure 5. More significantly, the terminal flash cast a sharp shadow of a sign pole across the paving, which can be clearly seen as a dark diagonal line on the left of the image. Since the direction of this shadow was diametrically opposite the location of the flash, the exact direction was determined by calibrating the image using the same procedures as for the Ottosdal and Gaborone videos, and using astrometric images taken later by Dr Oliver Moses of the Okavango Research Institute (ORI) of the University of Botswana in Maun to give us a vector from the west.

Meanwhile Peter Jenniskens had travelled to Maun just days after the impact, even before the possible fall location sites settled on the CKGR, where he had teamed up with Oliver Moses. They located excellent footage in Rakops which showed measurable shadows inside a restaurant, and gave us a further vector from a location east of the explosion. Before the author's arrival, Peter also located images of shadows on the roof of one of the buildings of Maun Lodge in Maun, which showed the direction of the fireball only a short time before peak brightness. This video would later be used to give further confirmation of the direction.


*Fig 5. Screen grab from Ghanzi Engen garage. The passage of the bolide was seen reflected on the roof of the dark vehicle, and a sharp shadow from a sign pole can be seen diagonally across the paving at left. The direction of the shadow was determined by marking a line across the tiles, placing a camera on the line and imaging the pole which caused the shadow along with background stars in the same way as in Figure 4b.*

*Fig 6. Team members during our initial meeting on June 12, 2018 at Okavango Research Institute (ORI), University of Botswana; left to right, Tim Cooper (ASSA), Dr Oliver Moses (ORI) and Dr Peter Jenniskens (SETI Institute).*

With the team now fully assembled we focused the next few days on searching for other video footage in Maun that would track the meteor longer (Figure 6). Most security camera systems only archive data for seven or fourteen days, so we needed to locate what we could to refine the location of the explosion and narrow down the footprint of the strewn field. Numerous other videos were found in Maun, none of which cast measurable shadows. We puzzled for some time why the Maun videos did not show shadows despite the location being relatively close to the meteor, and finally found the explanation while collecting eye witness accounts of the bolide. One eye witness (Mr Pambano, see below) said it was partly cloudy, and he saw the bolide moving in and out of the clouds. Therefore if the terminal flash occurred while the bolide was obscured by clouds, the light would have been diffused, resulting in no discernible shadows. This was not the case in all the other locations, which appear to have had cloudless skies.

Satisfied that we had exhausted all possibilities of locating any more useful footage, we had calibrated the most useful videos resulting in a set of vectors from different directions, as shown in Figure 7. The intersection with the predicted path showed good coincidence and enabled us to accurately determine the location of the potential strewn field in the northern region of the CKGR.

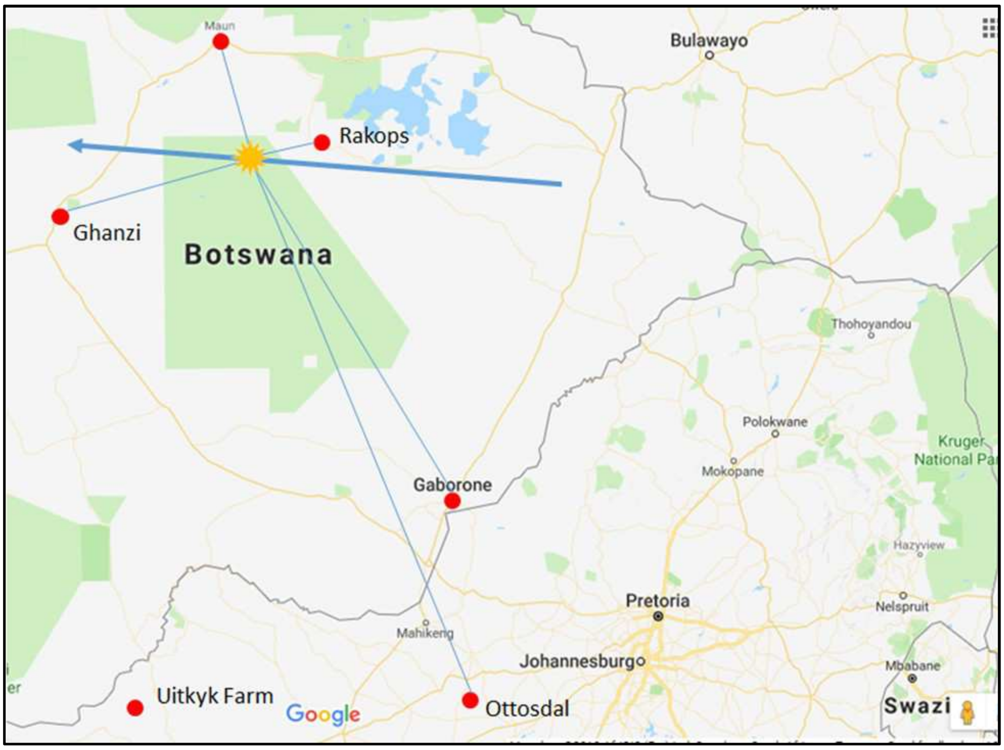


*Fig 7. Plot using Google Maps showing azimuth vectors of flash (yellow) after calibration of video images from Ottosdal, Gaborone, Ghanzi, Maun and Rakops. Path of the meteor is shown as a blue arrow. Map intends to show the general position only in the northern part of the Central Kalahari Game Reserve (light green area), though the actual position was determined with much greater accuracy than shown.*

**Eye-witness reports of the bolide**

In addition to video footage we collected numerous eye witness reports of the bolide, locations of which are shown in Figure 8. These reports clearly fall into two distinct groups, locations #1-6 at some distance from the explosion, and #7-11 in closer proximity to the explosion. Several reports were collected from location #11, in the town of Maun and vicinity. While all these reports were of limited use in defining the exact location of the strewn field, they nevertheless provided important details not seen in the videos.

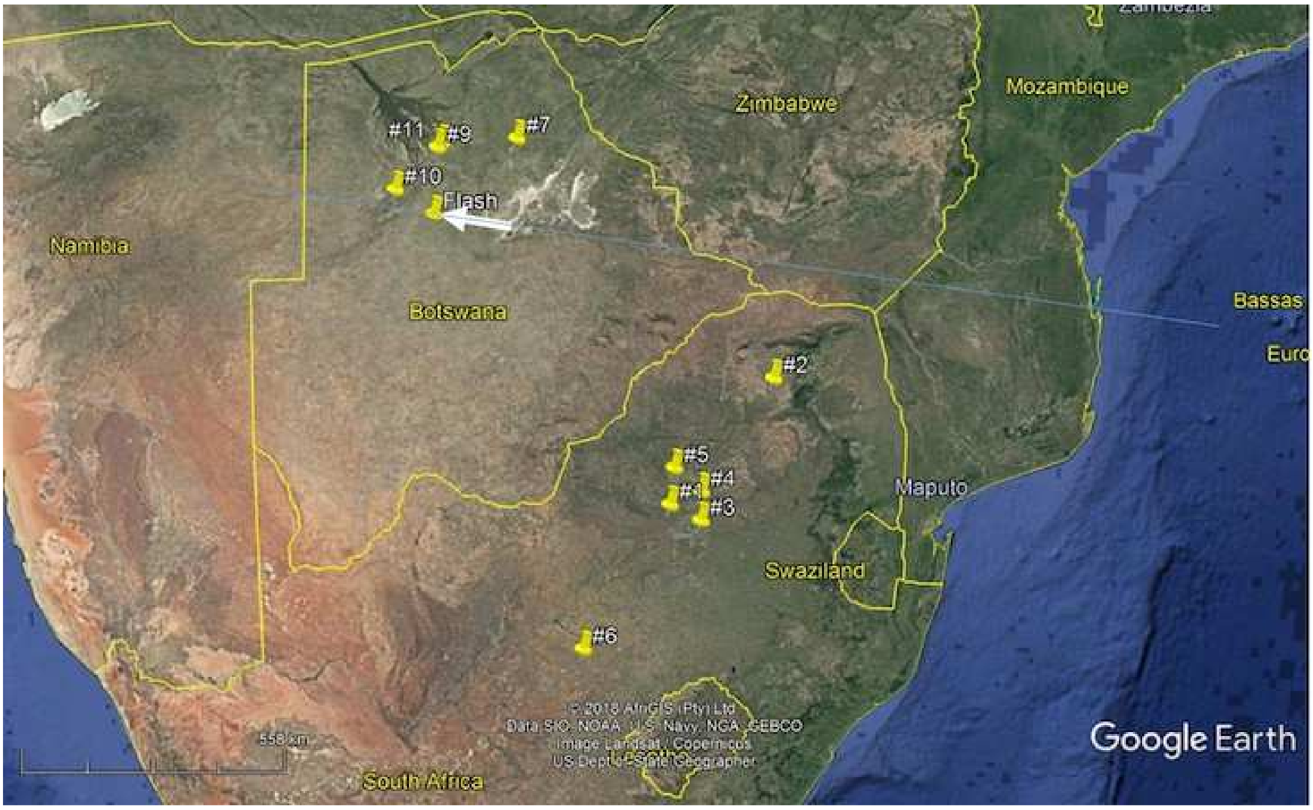


*Fig 8. Locations of important eye witness reports. The blue line shows the direction of the path across southern Africa; the white arrow shows the extent of the visible passage from eye-witness reports. Image courtesy Google Earth.*

The first report was received via the ASSA sightings webpage just eight minutes after the event, at 16h53 from **Julian Naik** (location #1). He was staying at the Maropeng Hotel and 'looking west at 16h45 saw a big fireball, with comet-like appearance and a long tail, that fell quickly to earth behind the mountains with a large flash on impact [sic]. Did not see the impact because it was behind the mountain. The object fell from the top right to bottom left and was bright red, white, orange. There was no moon and clear skies. No sound heard but there was a flash when it presumably impacted the ground'.

Shortly afterwards, **Jacques Naudé** (#2) from near Polokwane reported 'I saw it coming down slowly, lasted about 4 seconds, very much slower than a normal shooting star, it was red. I thought it had finished, but then I saw it continuing underneath a tree which was obscuring it half way. Then I saw a big flash on the horizon'. Jacques gave the direction as 295°, which is exactly the direction the flash would have been seen from his location as derived from video astrometry. As it turns out Jacques was actually no further from the predicted path than those in Maun, but the asteroid had not yet dipped sufficiently into the atmosphere for the ablation process to commence.

Airline pilot **Tarryn Lush** (#3) was on final approach to runway 3 at OR Tambo International and got a spectacular view of the bolide, appearing first as a green glow coming from a north-easterly direction, and ending in a bright orange explosion towards the west 'as it apparently descended into an inversion layer or low cloud'. She thought it may have fallen in the vicinity of Ventersdorp or Lichtenburg.

Just north of Pretoria, **Dr Rasigan Maharajh** and his daughter **Xera** (#4) had a good view of the bolide from the northern slopes of Meintjieskop. They reported a bright greenish-red fiery light heading towards the ground, and lost sight of it behind the Wonderboom/Magalieskruin ridge towards the north west, after which a wave of red, yellow and green light came from where it appeared to have landed. The whole event was over in just a few seconds.

Further to the west, **Mike Young** (#5) witnessed the explosions from Sediba Lodge near Brits. He did not see the visible path of the meteor but witnessed two almost simultaneous bright flashes of orange light tinged with red on the horizon below Gemini, the first slightly to the right and the second to the left, just below Castor and Pollux. The azimuths of the two stars were then 314° and 312° respectively. The actual azimuth of the flash as seen from this site would have been 320°.

The most southerly report came from **Johan Pretorius** (#6) who observed from 16km south of Bultfontein, Free State. 'Very bright object entered the atmosphere traveling in a northwest direction, disappeared behind a small ridge blocking our view. Moments later the north-western sky was lit up by what seemed to be an explosion. Even the horse started running when the object streaked over the sky! The approximate time (±90 seconds) was 16:45. We stood quietly for about 2-3 minutes to hear if we could make out a sound. However, we didn't hear anything'.

Reports #7-11 saw the bolide from north of the path, so the passage was from left to right. **David Grant Luck** (#7) was at Nxai Pan National Park and saw the bolide start just lower right of Crux, possibly about azimuth 187° from a sketch provided, descending towards the WSW at an angle of 15-20°. He said he lost the object amongst trees but thought it disappeared before it reached the horizon. The fireball lasted 5 seconds and colour started as intense white but changed rapidly to orange, blue, and green with lots of ‘sparks’ coming off it. ‘We all waited in anticipation for the sonic boom but nothing was heard’.

**Trevor Sutherland** (#8) was one of the best placed to see the demise of the bolide up close. He was on his way to a fishing trip, sitting in the front passenger seat driving on the A3 in a westerly direction towards Maun, and about 60km from the town, giving his location as approximately 20°11' S, 23°58’ E, when the fireball passed him on his immediate left. The flash lit up the landscape as daylight so that individual blades of grass were visible. Following the flash, a red glowing ball appeared to continue moving in the direction of Maun, and appeared to disappear on the horizon. Others in the vehicle who only saw the flash thought it was lightning. No sounds were reported, but the observer was inside a closed vehicle.

**Shane Seaman** (#9) a ranger at Sitatunga Camp was in dense bush and so did not see the actual meteor. ‘I saw a different white light spread over much of southern to SSE area of the horizon. There was no sound. Looking at the light I would say it moved from south toward SSE direction. It was probably one to two seconds long’.

To the west of the flash, Mr. **Gawele Phalane** (#10) was at the village of Semalo, about 140 km from Maun on the A3 towards Ghanzi. ‘Sitting outside it first appeared like a bulb, gradually brightening and was an amber colour. It exploded with a roundish shape. Followed by 3 flares, first huge, the second less bright, the third less bright again. Explosion had a sound like ammunition exploding "twaa-aa-aa" while it was seen. There was a persistent glow for about 5 seconds’.

During the team’s stay in Maun, and while awaiting allocation of permits to search for meteorites, we collected several reports from Maun and its environs (#11). One of the most important was from Delta Waters International School, which we visited looking for security camera footage. They did not have any, but we were able to interview the vice Principal **Mr Pambano** who saw the bolide clearly as he was sitting outside by the fire with friends, facing the direction of the fireball. The evening was partly cloudy, and suddenly he saw it coming out of the clouds. It continued above the clouds, moving in an out, each time shining brightly like daylight, and then ended in a bright flash. Mr Pambano said it flashed at least twice, possibly more, and disintegrated towards the end; ‘It ended making a lot of stars around; it was a bunch of smaller ones. Colours were mostly fire like, reddish, and amber. Can't remember hearing a sound. Moved quite a long distance. Didn't see afterglow’. Mr Pambano’s comment that the sky was partly cloudy and the bolide moved in and out of clouds finally explained why there were no shadows in most (but fortunately not all) of the videos located in Maun.

Another reliable sighting was from **Rod Bateman and Rob Jackson** who saw the bolide while sitting on the veranda in Maun, Botswana, looking south, they saw a bright white light with a trail behind it traveling across the sky from east to west. Duration of passage was 3-4 seconds. The fireball got bigger and brighter before disappearing below the tree-line, just west of south. As a result they did not see the actual explosion of the body, but did witness the resultant bright flash of light. Colour was described initially as bright white with a tinge of yellow, moving to red before disappearing from view. No sounds were heard.

During our time in Maun, we stayed at **Mokoro Lodge**, and realising the office entrance pointed in the right direction to see the bolide we asked the ladies on reception if they had witnessed the fireball. Sheila and a colleague were working at the reception desk when the bright light caught their attention. She got up from her position to take a closer look and saw the fireball explode in about the direction of a distant cellular communications tower, which we determined to be precisely in azimuth 182.9°. This direction agreed exactly with the direction of the flash as determined by astrometry.

Finally, **Jeanett Wellio** interviewed at the Caltex petrol station, said she was outside at home in Boseja, Maun, when the fireball lit up the sky. She said ‘it was sparkly, white, beautiful, something I have never seen in my life. Heard "sssh" sound when I saw it. There was a second flare then it diminished’.

These eye witness accounts enabled us to make a few tentative conclusions:

1. The various directions after converting into azimuths are consistent with the position of the flash as determined from video calibrations. They indicate the path travelled across earth’s surface as a visible bolide was quite short (white arrow in Figure 8) above central Botswana. Any observations from South Africa were at some distance and low altitude, despite the passage just north of Mussina, at which time ablation had not yet commenced.

2. Colours reported describe the meteor initially as white with a tail, while those observing from inside a lit room saw the meteor as a "green glow". The meteor then turned orange (amber) and exploded with a red glow. Note that there were no reports of white from the more distant locations, where the meteor was not quite as bright.

3. We ascribed the observation by Trevor Sutherland that a fiery red ball continued in the same direction after the flash to fragments emerging from the explosion. There were several reports of fragmentation near the terminal flash. The main explosion had three flares, the first being the strongest. A persistent glow remained for 5 seconds.

4. Sounds were reported from only two locations. Mr. Gawele Phalane (#10) at Semalo heard a sound like ammunition exploding "twaa-aa-aa", coincidental with the explosion, while at Boseja, Maun a "sssh" sound was heard at the same time as the meteor. Others interviewed in the Maun area did not hear any sounds, including rumbling noises like thunder sometime after the event. One location in South Africa reported hearing a dull thump one second later, but this must have been a coincidental noise unrelated to the bolide.

**Calibration of brightness of the bolide**

There were a number of discordant reports about the brightness of the bolide, varying from brighter than the full moon, to as bright as the sun at the moment of explosion. This discordancy is common for very bright fireballs due to the absence of bright objects with which to make a proper comparison. For example, the full moon has an apparent magnitude of around –13, while that of the sun is –27, a difference of 400,000 times in brightness with no convenient comparison objects in between.

The apparent brightness of the bolide can be measured fairly accurately however by comparing its brightness with that of terrestrial objects such as street or security lights, providing the magnitude of these objects can be accurately determined after passage of the meteor. Fortunately the passage of the bolide was captured in the security camera footage from Gaborone along with a number of bright security lights (Figure 4a). Accordingly the author travelled back to Gaborone at a date when the moon was situated directly above the scene. Since the magnitude of the moon is known with accuracy for any date and time, it was used as a standard to determine the brightness of the lights in Figure 4a, using the methods of reverse binocular photometry and digital aperture photometry. The author has reported on the reverse binocular method extensively in the past (see for example Cooper 2004) to measure the brightness of the moon during a lunar eclipse, by diminishing the size of the moon and comparing the brightness of the attenuated moon to bright stars and planets seen without attenuation. For the aperture photometry, images were taken of the lights and moon with a Nikon D3100 DSLR camera, selecting exposure conditions to ensure no saturation of individual pixels, and then measuring the integrated pixel values across the image using the Astroart 5.0 program from M.S.B. Software. Comparison of the summed pixel values of the security lights with that of the moon as standard enabled us to derive the apparent magnitude of the lights, which then served as standards for measurement of the apparent magnitude of the bolide.

The two techniques gave a good agreement of the brightness of the lights, which were determined in the region of $m_v$ = –8.5 to –9 for individual lights. Using these values, and with further data points derived from shadow densities in images from Maun, Peter Jenniskens determined the light curve shown in Figure 9. The bolide became visible at an altitude around 100 km when the apparent magnitude was –8, steadily increased in brightness to around magnitude –15, i.e. brighter than the full moon, just before disruption, and reached magnitude –23 during disruption, following which it faded rapidly. The measurement of the brightness exceeding –17 confirms the object as a super-bolide.

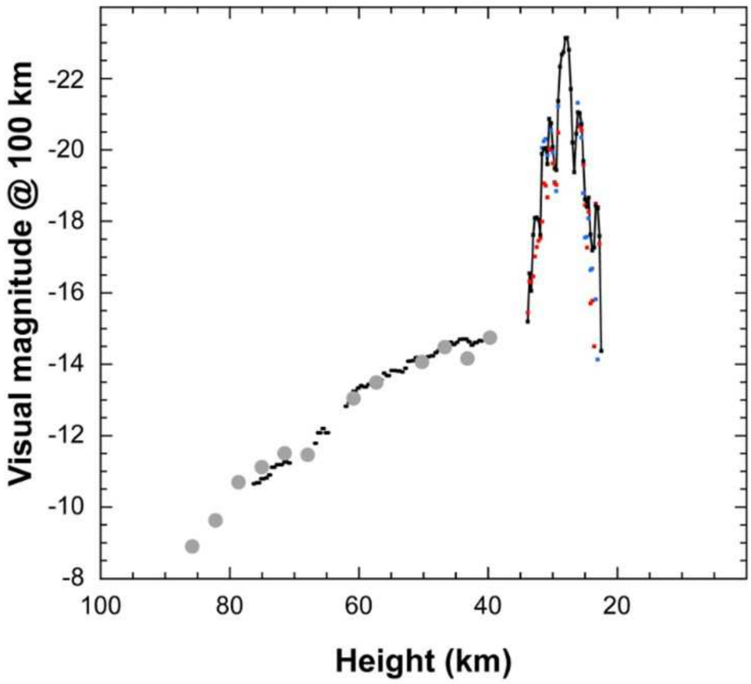


*Fig 9. Light curve of the bolide from 2018 LA normalised to a distance of 100 km, determined from calibration by the author of lights in the Gaborone footage (Figure 4a) and by Jenniskens from shadow densities in images secured from Maun. The brightness reaches nearly magnitude –15 during flight, and peaks at magnitude –23 at the point of disruption. In comparison the magnitude of the sun is –27, and the full moon around –13. Diagram courtesy Dr Peter Jenniskens.*

**Search for fragments of 2018 LA**

Following our initial astrometry, which resulted in pinpointing the location of the explosion as shown in Figure 7, a search was mounted which resulted in the discovery on June 23, 2018 of a single fragment from asteroid 2018 LA, weighing 17.92 grams and shown in Figure 10 (McDonald 2018). Unfortunately the author was unable to join this first expedition, as due to the time taken for the initial search permits to be granted, he had to return home to attend to pressing business issues. In the following weeks several expeditions were mounted by others but resulted in no further discoveries.

*Fig 10. Meteorite MP-1 from asteroid 2018 LA, found during the first search expedition on June 23, 2018, and weighing 17.92 grams. Image courtesy Dr Peter Jenniskens.*

Seeing that this single fragment was insufficient to allow a full characterisation of the meteorite, and consequently of the original asteroid, Peter Jenniskens proposed a final search in October 2018, before the onset of the summer rains. By that time it had been determined that the meteorite belonged to the HED group and a previous fall of that type in Turkey had resulted in mostly small meteorites. Jenniskens suggested to search for small 2-5 gram meteorites this time around. We revisited the astrometry in attempts to bring greater accuracy to the asteroid disruption point. Based on this, Davide Farnocchia at JPL recalculated the asteroid trajectory in the atmosphere, from which we calculated the fall locations. With this improved set of coordinates for the strewn field we worked with Dr. Mohutsiwe Gabadirwe from the Botswana Geoscience Institute (BGI) to arrange a new expedition to search for additional fragments (Figure 11).

Our original team comprising Oliver Moses, Thebe Kemosedile, Peter Jenniskens and Tim Cooper met up again in Maun on the morning of Monday October 8, 2018 and prepared for several days in the field. The location of the strewn field is extremely remote, in the northern Central Kalahari Game Reserve (CKGR) in the vicinity of Motopi and Passarge Valley camps, and all provisions had to be taken in, including food and water for the duration of the expedition.

*Fig 11. Team members from the October 2018 expedition. Standing left to right Tim Cooper (ASSA), Oliver Moses (ORI), Mohutsiwe Gabadirwe (BGI), Thebe Kemosedile (ORI), Sarah Tsenene (DWNP), Kabelo Dikole (BGI), Mosarwa Babutsi (Botswana National Museum, Gaborone), kneeling Kagiso Kgetse (DWNP) and Peter Jenniskens (SETI Institute). ASSA = Astronomical Society of Southern Africa, BGI = Botswana Geoscience Institute, ORI = Okavango Research Institute of the University of Botswana at Maun, DWNP = Department of Wildlife and National Parks (Photo by team member Odirile Sempho).*

After spending the morning shopping for provisions we entered CKGR at the Tsau entrance gate, and after driving for a couple of hours set up Camp 1 as evening twilight was descending. By now more searchers had arrived, including teams led by Dr Gabadirwe and by Mosarwa Babutsi from the Botswana National Museum, Gaborone.

The Central Kalahari Game Reserve is the largest game reserve in Botswana, the most remote in Southern Africa, and home to several species of predators including leopard, cheetah, spotted and brown hyena, wild dogs and the famous black-maned lion (information courtesy [www.discoverafrica.com/blog/a-short-guide-to-the-central-kalahari-game-reserve](www.discoverafrica.com/blog/a-short-guide-to-the-central-kalahari-game-reserve)). Dr Gabadirwe had kindly arranged our search permits, and was accompanied by two park rangers from the Department of Wildlife and National Parks, Sarah Tsenene and Kagiso Kgetse. That night as we sat around the camp fire, we were rewarded with a couple of spectacular long-pathed earth-grazing October Draconid meteors, remnants of comet 21P/ Giacobini-Zinner, which shower was to undergo an outburst later that night.

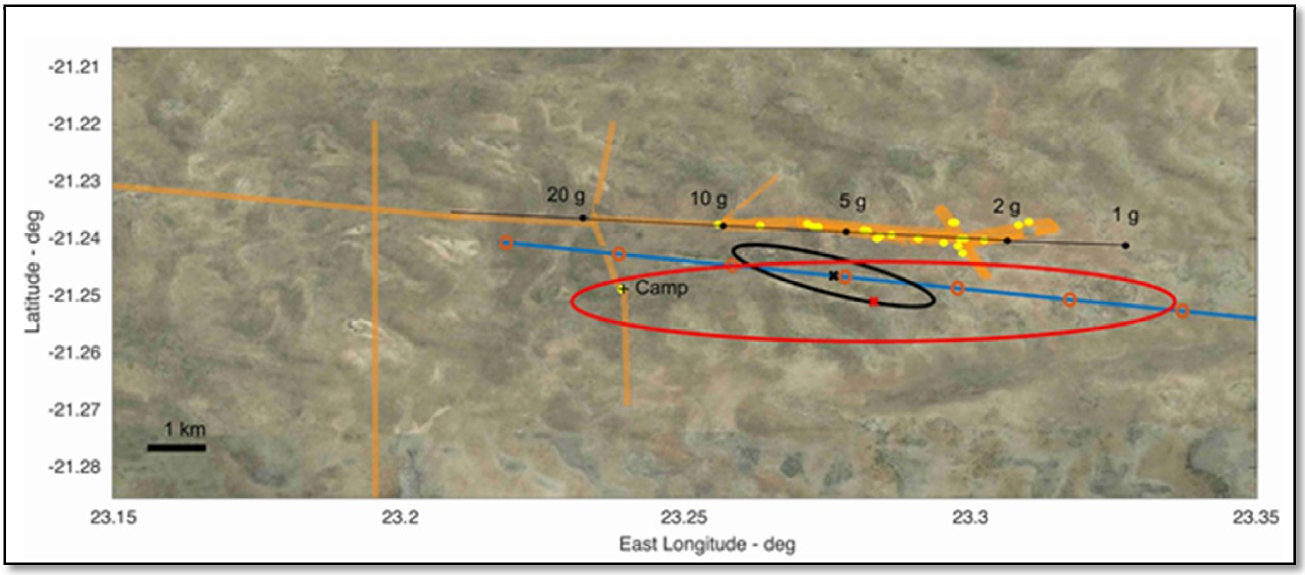


*Fig 12. Search areas and locations of meteorites found during the October 8-12, 2018 expedition. Position of Camp 2 nearby strewn field is shown. Blue line is the projected ground track of the asteroid with orange circles at 10-km altitude intervals. The black cross and ellipse show the position and 1$\sigma$ uncertainty of the asteroid position at time of disruption. Red dot and ellipse is the location and 2$\sigma$ uncertainty of the disruption as determined by video astrometry. Orange shading shows the areas searched as recorded by GPS. Yellow dots are locations of found meteorites. Diagram courtesy Dr Peter Jenniskens (Figure 14 in Jenniskens et al. 2021).*

After an early breakfast we headed for the coordinates indicated by our improved astrometry, and spread out along a fence with each person separated by about 20 metres, began to search along a path aligned with the passage of the bolide (Figure 12). Within 30 minutes of starting our search we had our first discovery, made appropriately by Dr Gabadirwe (see Figure 13 left). He announced the find by a clapping of hands, which became the signal for every further discovery made. The find location is the yellow dot immediately to the left of the 10g label in Figure 12. The meteorite was logged with exact discovery position, photographed and packaged, and preserved for later analysis. Day 2 ended with the satisfaction of knowing that our astrometry was accurate and we were now very close to the centre of the strewn field.

*Fig 13. One meteorite and two imposters. Left, meteorite MP-2 found by Dr Gabadirwe on 2018 October 9. This was the second fragment found from 2018 LA. Note the dark, shiny appearance. Centre is a piece of charcoal from a recent bush fire. Right is a Gemsbok dropping. The field was strewn with many of the latter two, but fortunately there were no terrestrial stones on the surface, which simplified final identification of suspect objects as meteorites.*

On Day 3 (October 10) we moved early morning from Camp 1 to Camp 2 (see Figure 14) to be close to the location of the previous day’s finds, and so that we could maximise the time searching for meteorites. On this day we extended the search eastwards between the locations where we expected to find fragments in the range 5-10 grams, resulting in two further finds near the expected mass range. This time it was Oliver Moses who found number 3 and Thebe Kemosedile who found number 4. We started to notice that the meteorites did not look the same. While Mohutsiwa Gabadirwe's find was black and shiny, Thebe Kemosedile's find was dull brown and had a checker board pattern.

*Fig 14. View of Camp 2, located close to the strewn field, and set up to maximise time searching for meteorites.*

On Day 4 we extended the search in both north and south directions, roughly perpendicular to the trajectory to determine whether the strewn field was wider, but the absence of any finds in both directions constrained the width of the strewn field close to the black (centre) line in Figure 12. Returning to searching again close to the centre line the team made a further eight more finds.

With the dimensions of the strewn field now confirmed, we spent Day 5 concentrating near to the centre line searching for additional fragments in the 1-10 gram mass range. That last day doubled the number of recovered meteorites by adding eleven more.

*Fig 15. View over the strewn field showing the type of terrain, predominantly grassland, with occasional small bushes and trees, and frequented by wild animals.*

During the five days we continued the search for eight hours each day, during which the daytime temperatures were near 40°C. The type of terrain can be seen in Figure 15, with typical desert grassland, with no shade for protection from the sun. The ground temperature was hot enough to melt the adhesive of my hiking boots, and by the third day both soles had completely delaminated! (Figure 16). Searching was not an easy task; there were lots of things that looked suspiciously like meteorite fragments but were not (Figure 13 centre and right), and most of these were either small pieces of charcoal from a recent bush fire, or ubiquitous Gemsbok droppings, all of which needed to be inspected carefully without touching to avoid contamination. But it was probably this heightened sense of awareness that resulted in us making a further 22 discoveries in total.

*Fig 16. The authors hiking boots early into Day 3. By Day 5 both had completely lost their soles, delaminated as a result of the intensely hot conditions. Running repairs were carried out with a roll of duct tape.*

The author managed to discover one fragment of 2018 LA (Figure 17), but left it late on Day 5 to find it. Not long before the end of our search, by now pretty much resigning myself to the fact that I had searched for four solid days in intense heat without finding anything inorganic, picking my way through rough ground strewn with thorns, and without soles on my boots, I happened upon something which looked distinctly out of place. It was small and shiny, but more surprisingly had a very dark greenish colour, unlike the other fragments we found which were mainly black, but most importantly it was a stone! I called Peter over to take a look at it, and he confirmed I had found another fragment, weighing 6.2 grams and now catalogued as meteorite MP-19 (for a list of all found meteorites see Meteoritical Bulletin no.110, in preparation). Because MP-19 looked different than the others, that meteorite was later sampled and played an important role in the consortium study.

*Fig 17. Tim Cooper, and the discovery of meteorite MP-19. Weighing in at 6.19 grams, discovered shortly before the end of our last day in the field, 2018 October 12 at 15h38 local time. Note the different appearance of MP-19 compared to MP-2 in Figure 13, a fact which played an important role in the analyses and characterisation of the meteorite during the consortium study.*

By the end of Day 5 the team had found another twenty-two fragments from asteroid 2018 LA. Afterwards we talked late into the night around the camp fire, satisfied in the knowledge that not only had we located many more fragments from the bolide, we had located the centre of the strewn field from asteroid 2018 LA, and all our calculations and hard work had paid off.

**The Motopi Pan meteorite and possible origin in the solar system**

The paper in Meteoritics and Planetary Science (Jenniskens et al. 2021) describes the final asteroid trajectory, its shape and spin period, as well as the properties of the recovered meteorites and their possible source region in the asteroid belt. Asteroid

2018 LA, discovered on June 2, 2018 at 08h15m48s, was slightly elongated and came into earth's atmosphere spinning once every 4 minutes. It disrupted later that same day at 16h44m11.5 ± 3s, at an altitude of 27.8 ± 0.9 km, in position Lon. = 23.287 ± 0.057°E, Lat. = 21.251 ± 0.007°S. The breakup deposited meteorites in a strewn field for fragments of around 1-10 grams roughly 1.7 km long and 400 metres wide (Figure 12). A total of twenty-three fragments were found with a combined mass of 122.22 grams, now named after the nearby watering hole Motopi Pan. They were shown to be eucrite-rich howardites, with individual stones showing more affinity to basaltic and cumulate eucrites, others to howardites or diogenites, all part of the howardite-eucrite-diogenite (HED) class which originate from asteroid 4 Vesta (McCord et al 1970). Unlike the meteorite Sariçiçek that fell in Turkey, the material which makes up the meteorite Motopi Pan underwent a strong heating event, probably during the formation of the Veneneia impact basin around 4.2 billion years ago. This material was spread out during the subsequent formation of the Rheasilvia basin about 3.7 billion years ago. NASA's Dawn mission imaged the asteroid Vesta and recorded several young craters with visible ejecta blankets that could be dated from counting the number of later smaller impacts on those blankets. Based on those ages and how long the meteorite spent in space being bombarded by cosmic rays, a good candidate origin crater of the meteorite is the 10 km crater Rubria (Figure 18), which is situated on Rheasilvia basin ejecta on top of a topographic high. Unlike Sariçiçek, which is thought to have originated in the Antonia impact crater on the slopes of Rheasilvia, Motopi Pan was not contaminated by solar wind noble gases and spent the past billion years relatively undisturbed (Jenniskens et al. 2021).

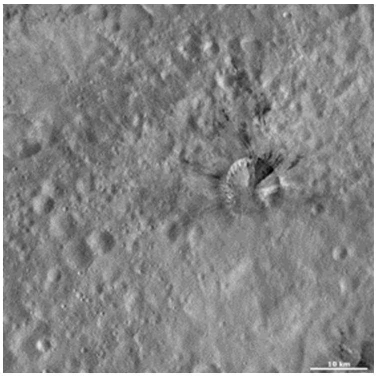

*Fig 18. Rubria Crater (upper right of centre) in the Rheasilvia Basin on asteroid 4 Vesta, probable source of the meteorites from 2018 LA. Image credit NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.*

**Conclusions and learning experiences for future very bright fireballs**

The appearance of the bright bolide on June 2, 2018 and ASSA's participation as part of a team investigating the potential strewn field location enabled us to gain vital experience in investigating very bright fireball events which potentially deposit meteorites. The following points should be noted in order to improve investigation of future events.

The criticality in obtaining sufficient measurable video footage cannot be over-emphasised. An intensive search for videos needs to be carried out from as widely differing geographical locations as possible to ensure accurate coincidence of the azimuth vectors. Since most security camera systems store their data for a fixed period on hard drive, typically seven or fourteen days, there is some urgency to locate this footage as soon as possible following the event before it is overwritten, and important information lost.

Excellent footage can be obtained from a number of sources including domestic security cameras, commercial properties such as shopping centres, factories and warehouses, and vehicle dash-cams. Petrol stations are good sources, but generally these cameras are pointing downwards onto the forecourt rather than upwards. However, they can record shadows of the bolide.

Both videos which capture the actual passage of the fireball or just shadows cast by objects in the video are useful. Both types need to be reliably calibrated by taking accurate still images after the event. These images need to be taken such that the aspect of the image is identical to the original video, and with sufficient star images to provide accurate astrometry. Frame grabs from videos which capture the actual fireball can be overlaid on and aligned with the calibration image to determine the coordinates of the path of the fireball, as well as the azimuth and altitude of events along the path. Frame grabs from videos with shadows can also be used to measure the azimuth of these events, which are in the anti-direction of the shadows cast.

Videos are also useful to measure the brightness of the fireball if they contain bright light sources such as street lights or security lights. These lights can be calibrated and used as standards with which to compare the brightness of the fireball along its path, enabling construction of a light curve.

Finally, it is important to gather a good number of reliable eye-witness accounts. While these are of limited value in accurately determining potential fall locations, they can provide important information in support of some effects seen in video records.

**Acknowledgements**

The author wishes to thank the following: Barend Swanepoel who made the original Ottosdal video and supporting information freely available, as well as Vicus and Sarina van Zyl, Tharina van Zyl and Barend Swanepoel senior for their grateful assistance during my visit to calibrate the video, moreover their wonderful hospitality, and especially to Sarina van Zyl for the delicious 'boerekos'. Beverly Lombard for access to her site and cameras and assistance in calibrating the video footage from Gaborone, and calibration of the security lights which contributed to the light curve of the bolide. Dr Oliver Moses, Okavango Research Institute, for arrangements in setting up the initial search team and permits, and negotiations with the authorities in Botswana, as well as travelling to Ghanzi to take the astrometric images used to calibrate the video from that location. Dr Mohutsiwe Gabadirwe for arranging permits for the October 2018 search expedition. Thebe Kemosedile, Okavango Research Institute, who was not only member of our search team, but shouldered the brunt of the cooking responsibilities in the field, with excellent results. Dr Peter Jenniskens, SETI Institute, for his mentorship over many years, for permission to use several of his images in this paper, and for comments made in its preparation. Jim Albers of the SETI Institute for assistance with calibration and astrometry of the Ottosdal video. Thanks to those ASSA members who directed me to various posts on the ASSA and Sterre en Planete Facebook pages, and forwarding reports submitted via the ASSA website, including Kos Coronaios and Willie Koorts. Last and not least to my wife Janet, with whom I travelled with friends Rob and Heather Patmore for a week's vacation in the Drakensberg the day after the impact. As more reports and video came in I left them high and dry in the Berg to continue without me while I went in pursuit of the remains of a small body from the asteroid belt. Thanks to all who made this a successful team effort!

**References**

Brown, P. (2009), University of Western Ontario, private communication dated November 30, 2009.

Chamberlin, A.B. (2018), Fireballs Reported by US Government Sensors, Center for Near-Earth Object Studies webpage at https://cneos.jpl.nasa.gov/fireballs/, accessed August 25, 2018.

Cooper T.P. (2004), *The darkness and colour of the umbra during a lunar eclipse*, *MNASSA* **63**, 60.

Cooper T.P. (2013), *The Daytime Bolide of 12 March 2013*, *MNASSA* **72**, 47-52.

Cooper T.P. (2017a), *Definitions of terms in meteor astronomy and recent Southern African Fireball Observations*, *MNASSA* **76**, 122.

Cooper T.P. (2017b), *The bright bolide of 2017 June 15*, *MNASSA* **76,** 2017, 218-231.

Gray W. (2018), in Pseudo-MPEC for ZLAF9B2 = 2018 LA, created June 3, 2018 at 16:04:49 UT.

Jenniskens P., Shaddad M. H., Numan D., Elsir S., Kudoda A. M., Zolensky M. E., Le L., Robinson G. A., Friedrich J. M., Rumble D., Steele A., Chesley S. R., Fitzsimmons A., Duddy S., Hsieh H. H., Ramsay G., Brown P. G., Edwards W. N., Tagliaferri E., Boslough M. B., Spalding R. E., Dantowitz R., Kozubal M., Pravec P., Borovicka J., Charvat Z., Vaubaillon J., Kuiper J., Albers J., Bishop J. L., Mancinelli R. L., Sandford S. A., Milam S. N., Nuevo M., Worden S. P., (2009) *The impact and recovery of asteroid 2008 TC3. Nature* **458**, 485–488.

Jenniskens P., Gabadirwe M., Yin Q-Z, Proyer A., Moses O., Kohout T., Franchi F, Gibson R. L., Kowalski R., Christensen E. J., Gibbs A. R., Heinze A., Denneau L., Farnocchia D., Chodas P., Gray W., Micheli M., Moskovtiz N., Onken C. A., Wolf C., Devillepoix H. A. R., Ye Q-Z., Robertson D. K., Brown P., Lyytinen E., Moilanen J., Albers J., Cooper T. P., Assink J., Evers L., Lahtinen P., Seitshiro L., Laubenstein M., Wantlo N., Moleje P., Maritinkole J., Suhonen H., Zolensky M., Ashwal L., Hiroi T., Sears D. W., Sehlke A., Maturilli A., Sanborn M. E., Huyskens M. H., Dey S., Ziegler K., Busemann H., Riebe M., Meier M. M., Welten K. C., Caffee M. W., Zhou Q., Li Q-L., Li X-H., Liu Y., Tang G-Q., McLain H. L., Dworkin J. P., Glavin D. P., Schmitt-Kopplin P., Sabbah H., Joblin C., Granvik M., Mosarwa B., and Botepe K., (2021) *The impact and recovery of asteroid 2018 LA*, *Meteoritics & Planetary Science* **56**, 844-893, online version (2021) at doi: 10.1111/maps.13653.

Matson R.D. (2018) *Minor planet impactor witnessed over Botswana*, posted on meteorite-list, 02 Jun 2018, 17:22:28.

McCord, T. B., Adams, J. B. and Johnson, T. V. (1970) *Asteroid Vesta: spectral reflectivity and compositional implications*. *Science* **168**, 1445–1447.

McDonald R. (2018), ed., *Fragment of Impacting Asteroid Recovered in Botswana*, NASA press release dated July 6, 2018, see https://www.seti.org/fragment-impacting-asteroid-recovered-botswana-0.

Russell S., Zipfel J., Folco L., Jones R., Grady M., McCoy T. and Grossman J. (2003), in *The Meteoritical Bulletin, No. 87, 2003 July*, *Meteoritics & Planetary Science* **38**, Nr 7, Supplement, A189–A248 (2003).

Williams G.V. (2018) MPEC 2018-L04 : 2018 LA. Issued June 3, 2018, 16:15 UT. Minor Planet Centre.

# Observations of the eta Aquariids in 2021

*Tim Cooper, Comet, Asteroid and Meteor Specialist, Shallow Sky Section*

## Introduction

The eta Aquariids meteor shower (IAU shower code ETA, shower number #31) is one of two meteor showers associated with comet 1P/Halley, and is the outbound debris stream of the comet after passing perihelion and coinciding with the descending node in its orbit. The other associated shower is the Orionids (IAU shower code ORI, shower number #8), which occurs at the ascending node, and which due to their visibility under more favourable circumstances from the northern hemisphere in late October are much better observed. Despite the fact the eta Aquariids are the most active meteor shower south of the celestial equator, the shower was for many years poorly observed by southern hemisphere observers. The radiant is less than one degree south of the celestial equator, only rises around 2am local time, and consequently has a narrow observing window of about two hours before dawn in which reliable determinations can be made of zenithal hourly rates (ZHR) without large correction factors due to low altitude. More recently this shower of fine, often spectacular meteors is beginning to attract increased attention, and we are beginning to understand more about the evolution of the debris stream left behind by comet 1P/Halley. Nevertheless, the eta Aquariids would benefit from more coverage and more ASSA members are invited to participate in future.

The author first observed the eta Aquariids on May 9, 1990, having just finished an early morning session of variable star observations, and gazing skywards as was customary before heading indoors, he saw 12 ETAs in a period of twenty minutes under clear skies with stars of magnitude 6.0 visible in the zenith. The overriding characteristic of these meteors was their brightness, and fast speed, with many of the brightest meteors leaving persistent trains. The mean magnitude was 2.0. With that casual observation came the decision to observe the eta Aquariids at every possible apparition in order to learn more about the shower. Since then the author has observed the eta Aquariid meteor shower every year, with the exceptions of the 1991 and 1996 apparitions which were entirely clouded out. The total observation time is over 250 hours, giving a data set of 2600 ETAs and 1625 other meteors, members of other showers and sporadic meteors, all of which were recorded with visual magnitude, apparent speed, perceived colour and tendency to leave trains. The analysis of this unique data set spanning three decades by a single observer will form the subject of a future article, and observations were made again in 2021 in support of that objective.

**Parent comet and the eta Aquariid meteor shower**

The parent of both the Orionids and eta Aquariids is comet 1P/Halley. The comet was named after Edmund Halley, who realised in 1705 that the comets seen in 1531, 1607 and 1682 were the same object, returning to the sun's vicinity every 76 years. Halley predicted its return again in 1758, and though he passed away fifteen years earlier, the comet returned as he predicted and now bears his name and the designation 1P as the first periodic comet discovered. The comet was however seen on many occasions previously, and was first recorded in Chinese records as early as –240 (BCE). Tracing the orbit backwards in time indicates the comet was probably perturbed into its current earth-crossing orbit after a close encounter with Jupiter around 220 revolutions ago (Yeomans 1986). The comet orbits the sun with a mean period currently around 76 years, was last at perihelion on 1986 February 9.45 (Yeomans 1983) and will next reach perihelion on 2061 July 28.72 UT (Giorgini 2021). Between apparitions the comet recedes to the farthest point in its orbit (aphelion) at a distance of around 35 astronomical units (au) from the sun. In fact the comet has not yet reached its furthest point on its way out after the 1986 apparition, and will only reach that point and turn for home on December 9, 2023 (Kronk). At each approach to the sun the comet comes under the influence of solar radiation, and heating causes sublimation of ices, principally carbon monoxide and water vapour, to form a coma. At the same time dust particles are released from the now-active nucleus, which are then free to orbit the sun as meteoroids (Figure 1). It is these particles which may be observed as meteors if they enter the earth's atmosphere, leading to the eta Aquariids if they occur at the descending node of their orbit in early May, and the Orionids at the ascending node in October.

*Fig 1. Comet 1P/ Halley showing ion and dust tails, photo by A H Jarrett and G J Malcolm (1987) during the 1986 apparition. The ion tail is seen as sharp rays on the left hand side of the image, and in colour images (see for example image by W Liller taken the same night in Sky and Telescope March 1987, p261) shows as blue due to fluorescence of $CO^+$ at 427.3nm. The remainder is dust, shining in the light of reflected sunlight. Image taken on March 22, 1986, 60 minute exposure starting at 01h03 UT. It is these dust particles which may be observed as eta Aquariid meteors if they enter earth's atmosphere.*

Ferrin (2009) has shown that there is a wide arc of the comet's orbit during which particles are emitted from the nucleus. The secular light curve in Figure 2 plots the total magnitude m1(1,R) of the comet against log R, which is the log distance of the comet from the sun in au. Closed circles are magnitudes of the nucleus, when there was no visible coma, and open circles are where there were visible signs of coma and the comet was active. The point at which the comet switches on, inferring sublimation has begun and presumably dust grains are released into the nuclear envelope, occurs at $R_{ON}$, which is at a distance of –6.15 ± 0.19 au from the sun. The minus symbol preceding the distance indicates it is before the perihelion point (q) in its orbit. The comet peaks in activity somewhat after perihelion, referred to as LAG, and is the difference in days between perihelion and peak brightness. The value is positive if peak brightness occurs after perihelion, and in the case of comet 1P/Halley amounts to 11.2 ± 0.1 days later than its closest approach to the sun. After perihelion and as the comet recedes in its orbit, activity decreases at a slower rate than the increase and leads to a belly in the light curve. Finally sublimation stops and the activity ends at $R_{OFF}$, which is at 12.56 ± 0.02 au. Curiously, examination of Figure 2 shows that after switching off the comet underwent a brief outburst in activity again at R=14.1 au. The outburst was short-lived and the reason is unknown. Given that the comet reaches R = 35 au at aphelion, the arc of its orbit in which the comet is releasing dust grains, ranging from R = –6.15 to 12.56, is considerable. With each successive return to the sun's vicinity the dust matrix builds up and the meteor stream grows in complexity.

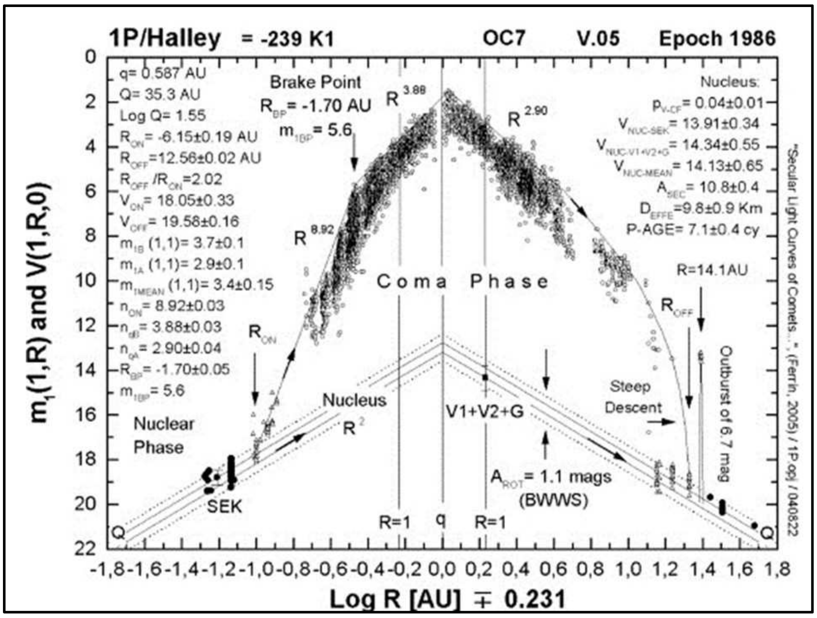


*Fig 2. Secular light curve for comet 1P/ Halley (Ferrin 2009) showing the distance of the comet from the sun when sublimation started ($R_{ON}$) and ended ($R_{OFF}$) for the last apparition. Perihelion is at q = 0.587 AU. Note the peak in brightness 11 days after perihelion, and the outburst of 6.7 magnitude occurring after $R_{OFF}$.*

Another aspect that can be seen in the secular light curve is the rotation of the nucleus. The magnitude of the nucleus (closed circles) varies with amplitude $A_{ROT}$ = 1.1 magnitude. Results from spacecraft (Keller et al 1994, Merényi et al 1990, Whipple 1987) indicate the nucleus is an elongated ellipsoid, with dimensions of approximately 15x7x7 km. The nucleus rotates around its major axis once every 7.4 days, but also precesses about an axis more or less in line with the ecliptic poles once every 2.2 days. The result is that the nucleus tumbles along in its orbit. There are at least three active jetting sites with different intensities, which eject dust from the nucleus as they move in and out of sunlight (Figure 3). Therefore, the original distribution of dust is expected to be rather inhomogeneous depending on which active nuclear regions were exposed to sunlight at any specific time. The changing nature of gas and dust emission from the nucleus of the comet is well seen in the selection of images taken by Jarrett and Malcolm (1987) and shown as Figure 4. They imaged the comet nightly with the 10-inch Metcalf telescope during the time it was well placed for observation from Boyden Observatory. These images show changes in jet structures, differences which are visible from night to night, as active regions on the nucleus moved in and out of sunlight.

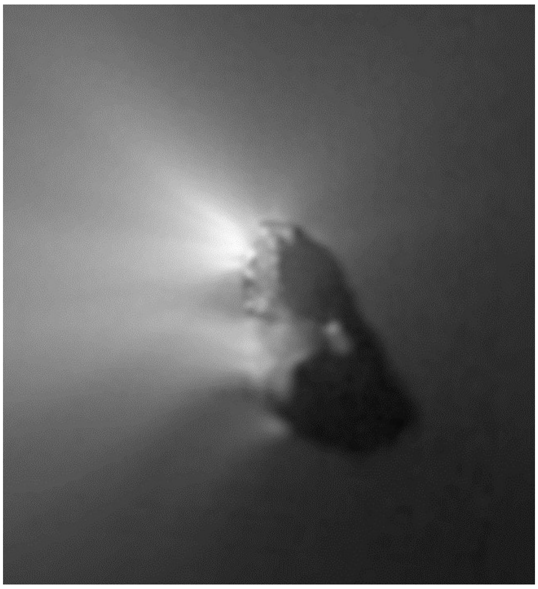

*Fig 3. Active sites on the nucleus of comet 1P/Halley. Image by the Halley Multicolour Camera onboard the Giotto spacecraft, taken on March 14, 1986 (Keller et al 1994). The HMC identified three active sites, with different intensities of dust emission, and which become active as they move in and out of sunlight as the nucleus tumbles in its orbit.*

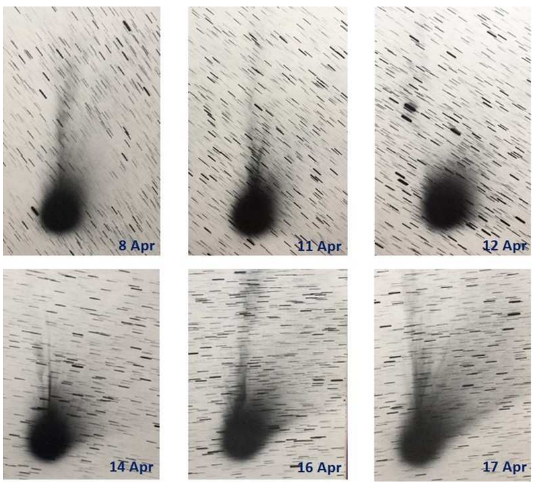


*Fig 4. Changes in activity within the coma and dust tail of comet 1P/Halley, from Jarrett and Malcolm (1987). Images not to scale, and intend to show changes in appearance only. Exposures (all times UT): 8 April, 43 minutes from 00h12; 11 April, 40 minutes from 00h46; 12 April, 45 minutes from 00h50; 14 April, 60 minutes from 22h10; 16 April, 45 minutes from 23h14; 17 April, 60 minutes from 21h00.*

Several models have been postulated as to the structure of the meteor stream laid down by comet 1P/Halley. The first was the 'shell model' of McIntosh and Hajduk (1983), who theorized that rather than being cylindrical in cross section, the stream is made up of flat ribbons, which build up in shells with each return of the comet. A few years later, McIntosh and Jones (1988) considered the contribution of planetary perturbations, solar radiation pressure and Poynting-Robertson drag on the ejected particles, which collectively broaden the stream and introduce fine structures. More recently Ryabova (2003) proposed the stream is made up of filaments formed by the initial distribution of orbits of ejected particles at each apparition, which build up over many apparitions, and are subsequently perturbed by close approach to the planets. Ryabova also stated the current observations of eta Aquariids cannot be from particles ejected after 837. Given the current miss distance between the orbit of the earth and comet 1P/Halley, it takes a considerable period for ejected particles to migrate into the earth's path.

The author drew attention to the complex nature of visual eta Aquariid activity following observations for example in 1993, when the rate increased unexpectedly to ZHR>100 on the morning of May 3 (Cooper 1996). Dubietis (2003) investigated the long-term activity from both the eta Aquariids and the Orionids, and concluded the activity might be cyclical with a period of 12 years. He also made reference to filamentary structures present in both Halley streams. Jenniskens (2006) concluded the activity profile of the eta Aquariids is asymmetric, and consists of a narrow component superimposed on a broader component, which no doubt results in the activity often observed for several days after the normal maximum. He concluded variations in the rate of the narrow component occurred depending on whether Jupiter was on the same side of the sun as earth in its orbit. Egal et al (2020) also investigated the activity of both Halley showers. For the eta Aquariids they concluded the shower is active between solar longitudes ($\lambda_{\odot}$) = 35-60, with highest activity occurring between $\lambda_{\odot}$ = 44-50, peaking with ZHR = 65-70. Outbursts occur due to encounters with meteoroids trapped in resonant orbits with Jupiter, as was the case in 2004 and 2013, when the ZHR exceeded 100. The latter outburst had been predicted by Sato (2013) following orbital modelling, which indicated the earth would make a close approach to filaments of particles ejected from comet 1P/Halley at its –910 and –1197 apparitions, and indeed enhanced rates were observed over a period of several days (Cooper 2013). Egal et al also concluded the mean activity curve for the eta Aquariids is asymmetric, with a faster rise and slower decline, but they found no evidence of any periodicity in activity.

The foregoing conclusions by several researchers confirm the complex nature of eta Aquariid activity, which is also seen in visual observations, though it must be emphasised that a paucity of observations in some years, often dependent on weather and compounded by a narrow observing window can lead to a lack of useful data. The eta Aquariids would benefit in general from increased coverage, especially from the southern hemisphere, in order to further improve the understanding of the meteor stream from comet 1P/Halley.

**Visual observations in 2021**

In preparation for the 2021 apparition the author was invited to give a presentation to the Johannesburg Centre of ASSA. This took place using the Zoom platform on Wednesday April 14 with a talk entitled 'Everything you ever wanted to know about the eta Aquariids…but were afraid to ask'. The talk outlined the background to the meteor streams from comet 1P/Halley, what to expect during 2021 and guidelines on how to observe the eta Aquariids. As a result, Andy Overbeek and John Lindsay-Smith travelled to a dark sky site near Warden, Free State, and contributed valuable observations for the mornings of May 5 and 6. Hopefully more individuals can be persuaded to join the observing effort in the future.

Conditions this year were expected to suffer some interference from moonlight. Last quarter moon occurred on May 3, and was still 36% illuminated and only 12° from the shower radiant on the morning of May 5. With a magnitude of –12 at the time, steps had to be taken to centre the field of view to the north of the radiant to avoid gazing at the moon and affecting adapted vision. Nevertheless, some fainter ETAs would have been missed around the mornings of maximum activity. Moonlight became less of a factor with each later morning, and after May 7 was of no real consequence. Observations were more affected this year by weather. Despite the fact that late April and early May usually give clear skies, after the ending of the Highveld rain season and before annual episodes of grass burning deteriorate seeing conditions, observations this year were limited by both factors. Rain and cloud continued right up to the end of April, including heavy rains and unseasonal thunder storms on the night of April 30/May 1, and the following night was entirely clouded out. Consequently observations only began on the morning of May 3 by which time the sharp rise in activity was already in progress. The author relocated to a dark sky site for the mornings of May 4-7 in order to negate the effect of the bright moon on seeing due to illumination of particulate emissions near home. Good conditions were experienced on the mornings of May 4 and 5, but May 6 was entirely clouded out. Fortunately, Andy Overbeek and John Lindsay-Smith had clear skies on the morning of May 6 which allows for confirmation of the rate on that morning. During two one hour sessions they saw 6 and 16 ETAs respectively, which under the seeing conditions reported translates to ZHR = 44 at $\lambda_{\odot}$ = 45.5. The morning of May 7 started cloudy, but cleared from around 3am local time, allowing three sessions, with only the first affected slightly by cloud. With the moon now moving away from the vicinity of the radiant, this morning gave the best observing conditions of the campaign.

Observations continued back at home and as weather permitted up to and including May 16/17, which enabled continued observation of the declining ETA rates, but also to determine whether there was any outburst of gamma Piscis Austrinids (GPAs), as was the case last year. May 18 onwards saw a return of heavy sky glow due to grass burning and consequently poor observing conditions, and brought an end to the 2021 campaign.

| **Date 2021** | **Time UT** | **$T_{eff}$ hours** | **F** | **LM** | **ETA** | **Other** | **Total** | $\lambda_\odot$ | **ZHR** |
|---|---|---|---|---|---|---|---|---|---|
| May 3 | 0124-0224 | 1.00 | 1.00 | 5.25 | 3 | 0 | 3 | 42.58 | 20.6 |
| May 3 | 0233-0303 | 0.50 | 1.00 | 5.30 | 3 | 2 | 5 | 42.61 | 28.4 |
| May 3 | 0303-0339 | 0.60 | 1.00 | 5.35 | 4 | 3 | 7 | 42.64 | 26.5 |
| May 4 | 0127-0227 | 1.00 | 1.00 | 5.70 | 1 | 1 | 2 | 43.55 | 4.1 |
| May 4 | 0227-0257 | 0.50 | 1.00 | 5.75 | 6 | 2 | 8 | 43.58 | 37.0 |
| May 4 | 0257-0330 | 0.55 | 1.00 | 5.80 | 4 | 2 | 6 | 43.60 | 18.8 |
| May 5 | 0129-0200 | 0.52 | 1.00 | 5.70 | 10 | 0 | 10 | 44.51 | 84.4 |
| May 5 | 0200-0230 | 0.50 | 1.00 | 5.80 | 4 | 3 | 7 | 44.53 | 26.4 |
| May 5 | 0230-0300 | 0.50 | 1.00 | 5.75 | 9 | 4 | 13 | 44.55 | 53.6 |
| May 5 | 0304-0334 | 0.50 | 1.00 | 5.65 | 7 | 3 | 10 | 44.57 | 40.3 |
| May 7 | 0204-0234 | 0.50 | 1.25 | 5.70 | 5 | 5 | 10 | 46.47 | 42.4 |
| May 7 | 0234-0304 | 0.50 | 1.00 | 5.90 | 9 | 1 | 10 | 46.49 | 44.7 |
| May 7 | 0304-0330 | 0.43 | 1.00 | 6.00 | 8 | 1 | 9 | 46.51 | 38.4 |
| May 9 | 0145-0240 | 0.92 | 1.00 | 5.30 | 7 | 5 | 12 | 48.40 | 38.2 |
| May 9 | 0240-0335 | 0.92 | 1.00 | 5.40 | 7 | 4 | 11 | 48.44 | 30.0 |
| May 11 | 0145-0230 | 0.75 | 1.00 | 5.25 | 3 | 3 | 6 | 50.33 | 20.9 |
| May 11 | 0242-0330 | 0.80 | 1.00 | 5.30 | 1 | 5 | 6 | 50.37 | 4.9 |
| May 15 | 0050-0138 | 0.80 | 1.00 | 5.25 | 1 | 6 | 7 | 54.16 | 8.0 |
| May 15 | 0157-0237 | 0.66 | 1.00 | 5.30 | 1 | 3 | 4 | 54.20 | 6.8 |
| May 15 | 0257-0337 | 0.66 | 1.00 | 5.30 | 1 | 1 | 2 | 54.24 | 5.6 |
| May 16 | 0118-0209 | 0.85 | 1.00 | 5.30 | 0 | 2 | 2 | 55.14 | 0 |
| May 16 | 0236-0324 | 0.80 | 1.00 | 5.35 | 1 | 1 | 2 | 55.19 | 4.7 |
| May 17 | 0216-0256 | 0.67 | 1.00 | 5.40 | 0 | 3 | 3 | 56.14 | 0 |
| May 17 | 0256-0336 | 0.67 | 1.00 | 5.50 | 2 | 2 | 4 | 56.17 | 9.5 |
| **Total** | | **16.10** | | | **97** | **62** | **159** | | |

*Table 1. Observation periods and conditions, number of meteors observed by session, and ZHR for ETAs. F is the correction factor for obscuration by clouds, LM is the faintest star visible to the naked eye during the watch, ETA is the number of eta Aquariids seen (N in the ZHR computation), Other is the number of all other meteors observed including minor showers and sporadic meteors, $\lambda_\odot$ is the solar longitude for the mid-point of the session. All observations from Gauteng, except May 4 to May 7 from Limpopo.*

## Rate profile for the eta Aquariids in 2021

The full set of observations is given in Table 1 , which gives dates and times of observing sessions, limiting magnitude, obscuration factor F for periods with clouds, and numbers of observed meteors. ETA rates for each period were converted to ZHR according to (1):

$$ZHR = \frac{N \times F \times r^{(6.5-LM)}}{T_{eff} \times \sin(h)} \qquad (1)$$

where:
- $N$ = number of shower meteors observed
- $F$ = obscuration factor
- $r$ = population index
- $h$ = mean altitude of radiant above horizon
- $LM$ = limiting magnitude, faintest star visible to the naked eye
- $T_{eff}$ = observing time in hours corrected for any breaks

The population index is a value which expresses the ratio of the number of meteors in subsequent magnitude bins, with lower values of r indicating brighter meteors. The range of r is typically in the region of 2.0 for showers with bright meteors, and 3.5 for faint meteors. To be consistent with the rate data in Egal et al (2020) the value of r was normalized to a population index of 2.46. Error bars were calculated from:

$$\Delta ZHR = \frac{ZHR}{\sqrt{N}} \qquad (2)$$

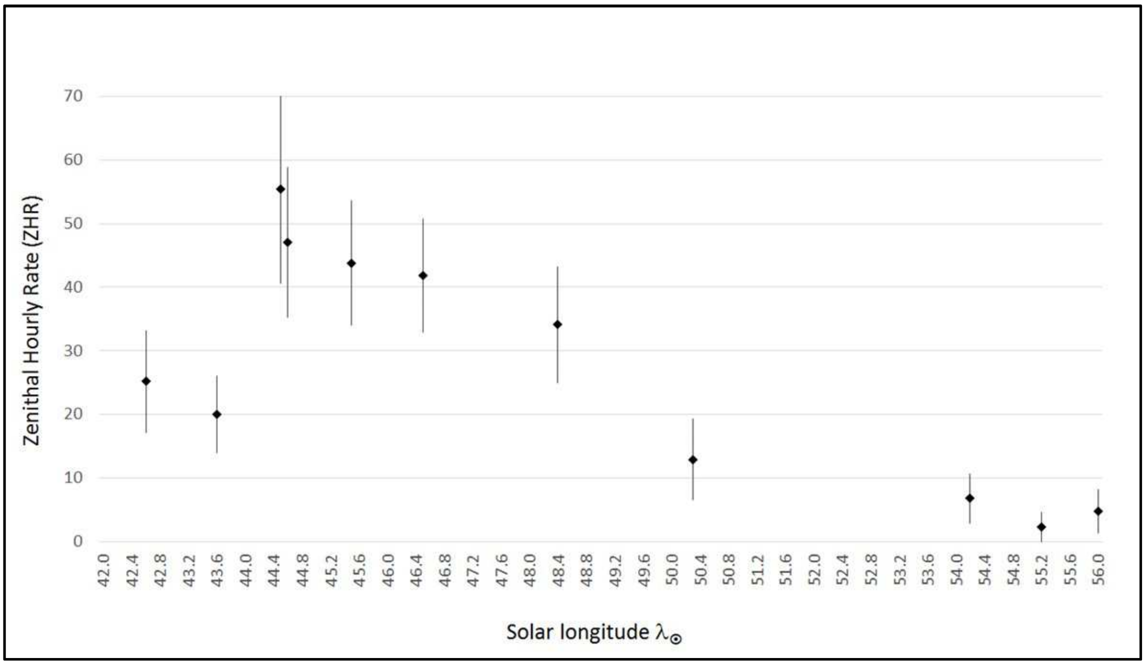


*Fig 5. Rate profile for the 2021 eta Aquariids based on observations by the author. The point for solar longitude 45.5° (morning of May 6) is from observations by Andy Overbeek and John Lindsay-Smith and confirms peak activity occurred on May 5. Two*

*points for solar longitude 45.5-45.7 show the rapidly changing rate on May 5, see expansion in Figure 6.*

The overall rate profile is shown in Figure 5. While unfortunately weather prevented observation of the early rise in activity, the asymmetry of the rate profile, with sharper rise to maximum and slower decline after maximum is evident. The maximum probably occurred on May 5, as Andy Overbeek and John Lindsay-Smith's observations indicate the decline was already in progress by May 6. Figure 6 shows rate profiles for the nights of May 4/5 and 6/7, and indicates a difference in homogeneity of the stream between the two mornings. ETA rates on both mornings were at similar levels, but the mean rate for May 5 was found to be higher as a result of a brief period of high activity, probably as the earth passed through a denser filament of meteoroids.

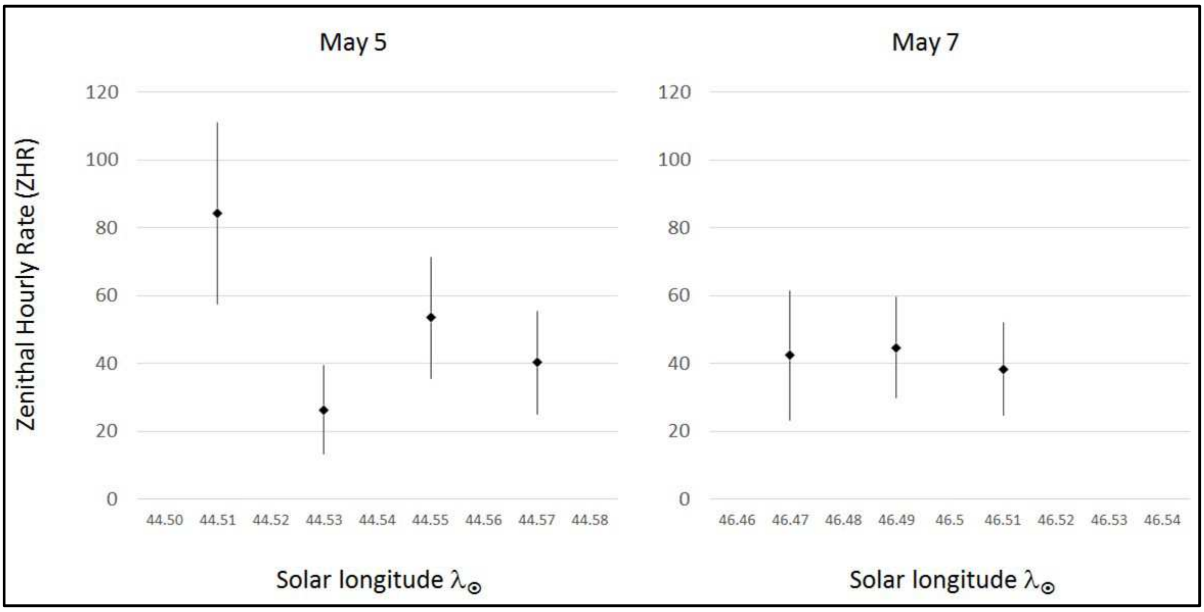


*Fig 6. Rate profiles for the mornings of May 5 and May 7. Note the rates for May 7 are consistent over three successive 30 minute periods, while for May 5 the rates indicate passage through a more dense filament around solar longitude 44.5°.*

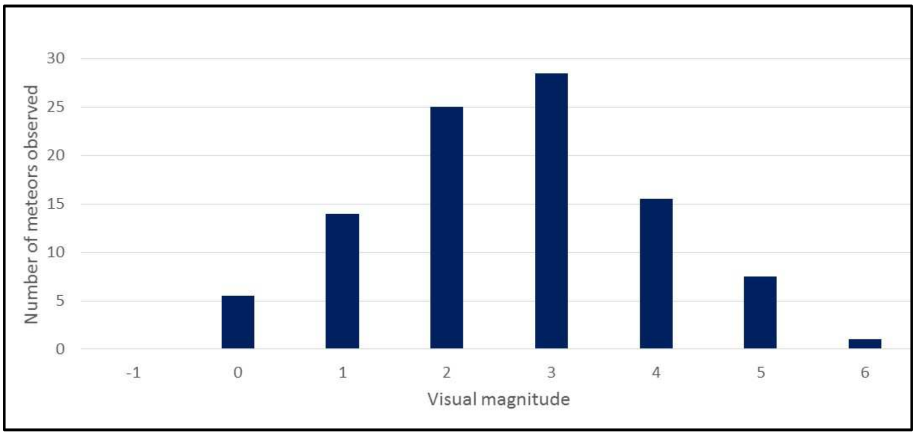


*Fig 7. Magnitude distribution for 97 observed eta Aquariids. Mean magnitude was 2.63. Note the absence of any meteors brighter than magnitude 0.*

Magnitude distributions for the 97 observed eta

Aquariids are given in Figure 7. The overall mean magnitude was 2.63, which is similar to 2018 (mean = 2.70, n = 149) and 2019 (2.55, 102), but fainter than 2017 (2.22, 56) and 2020 (2.18, 102), and also the outburst year 2013 (2.24, 256). No eta Aquariids were observed brighter than magnitude 0. The only period when the mean brightness exceeded magnitude 2 was the morning of May 4 ($\lambda_{\odot}$ = 43.58-43.60, mean = 1.80, n=10), when the earth probably encountered slightly larger particles. For now the brightness of the eta Aquariids in 2021 appears to have been towards the fainter side of the typical range, but any trends in the long term population index of the shower will be further explored in the thirty-year study.

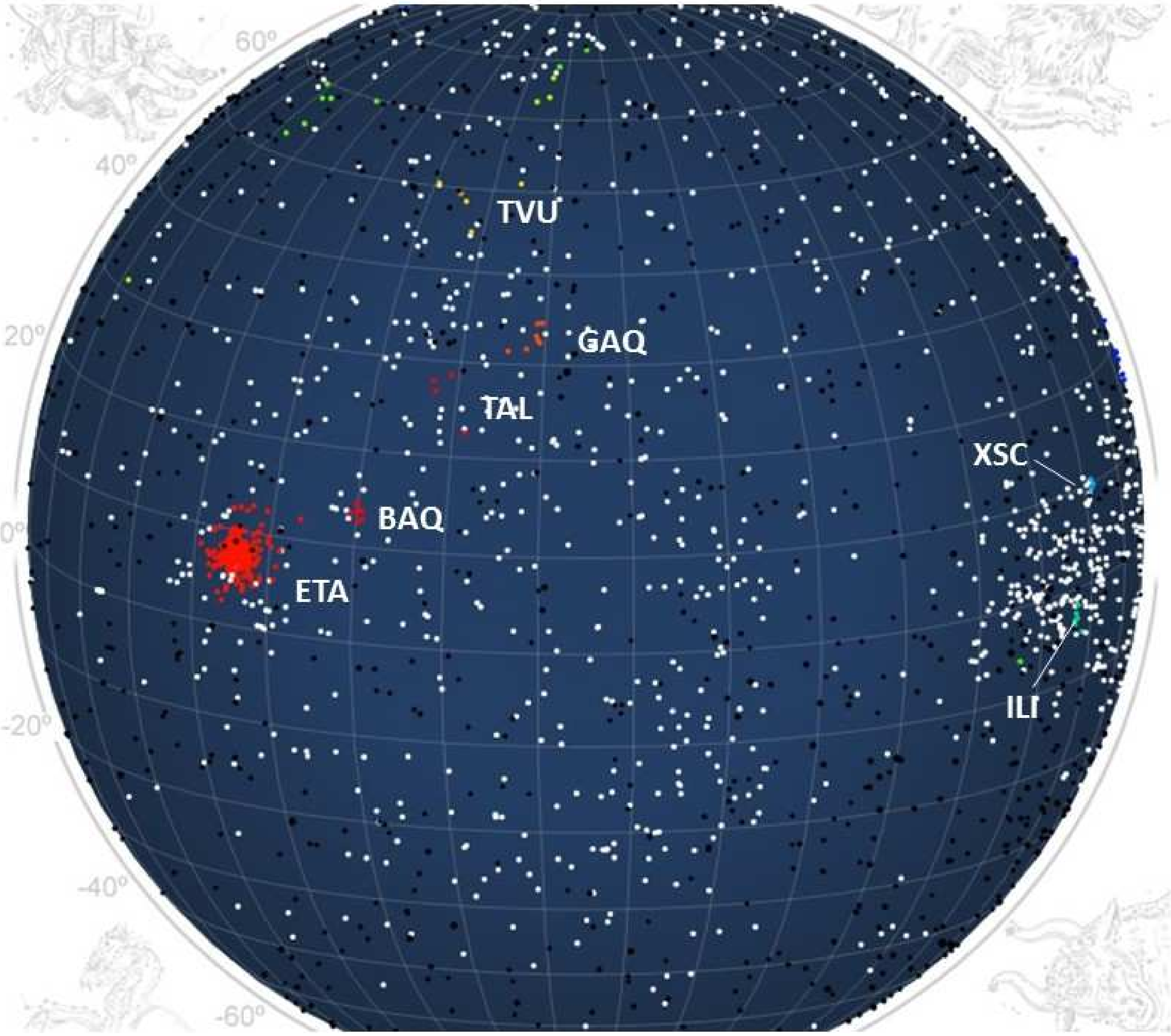


*Fig 8. Radiant activity for May 5, based on global CAMS video captures. Black dots are stars, coloured dots are shower meteors, colours indicate speeds, with red being fast meteors, blue being slow, white dots are sporadic or unclassified shower meteors. ETA = eta Aquariids, BAQ = beta Aquariids, TAL = 22 Aquilids, GAQ = gamma Aquilids, ILI = iota[1] Librids, XSC = xi Scorpiids, TVU = 21 Vulpeculids. The large concentration of white dots at right are mainly Anthelion (ANT) meteors.*

## Observations of concomitant activity

In addition to the eta Aquariids, several other minor showers are active during May mornings. Figure 8 shows the extent of showers active on the morning of May 5, based on global CAMS captures. Also on a number of occasions while observing the eta Aquariids in the past, activity was observed radiating from the vicinity of Piscis Austrinus, most notably in 2003, when in 2.0 hours on May 4 more than a dozen meteors were plotted from a radiant near 335°, -28°. Previously on May 16-18, 1997, several meteors were noted as radiating from 'near Fomalhaut', and a further ten possible members were recorded in 2013 (Cooper 2013). An outburst of meteors was detected by CAMS (Jenniskens 2020) on May 15 and 16, 2020 from a radiant at RA = $341.7 \pm 0.8°$, Decl. = $-31.0 \pm 0.4°$, and now confirmed as the gamma Piscis Austrinids (GPA, IAU shower number #1034). With these instances in mind, observations were continued until May 17 to determine whether the gamma Piscis Austrinids demonstrate annual activity. Only four GPAs were detected in 2021, three on the morning of May 15, one on May 16, and none on May 17. No observations were possible from May 18 onwards. CAMS globally did detect activity starting on May 14 and lasting up to May 19, but seemingly at a much lower level than last year. It therefore appears that the gamma Piscis Austrinids may show weak annual activity, but with occasional outbursts, and a watch should be kept on the possibility of further outbursts in the future.

## Conclusions

The eta Aquariids produced a fairly average performance in 2021, reaching ZHR ~$50 \pm 15$ on the morning of May 5, at solar longitude ~44.5°. The rate profile is asymmetric, with a slower decline after maximum. Some structures were noted within the stream, notably on the morning of May 5 when the rate exceeded ZHR = 80 for a brief period. Really bright members were noticeable by their absence and the observed eta Aquariids, with mean magnitude 2.63, were towards the fainter end of the range observed in recent years.

## Acknowledgements

Thanks to Magda Streicher for her unfailing friendship and motivation, assistance with the comet Halley images used in Figures 1 and 4, and support during visual observations in Limpopo. Thanks to Andy Overbeek and John Lindsay-Smith who travelled far to secure observations at a dark sky site, particularly on the morning of

May 6 when the author was clouded out, which added an important point to the rate profile.

## References

Cooper T.P., (2013) The 2013 Eta Aquariids from Bredell, *MNASSA* **72**, 186.

Cooper T.P., (1996) A decade of visual eta Aquariid meteor observations, *WGN* 24:5, 157-161.

Dubietis A., (2003) Long-term activity of meteor showers from Comet 1P/Halley, *WGN* 31:2, 43-48

Egal A., Brown P. G., Rendtel J., Campbell-Brown M., and P. Wiegert P., (2020) Activity of the Eta-Aquariid and Orionid meteor showers, *A&A*, **640**, A58, doi:10.1051/0004-6361/202038115.

Ferrin I., (2009) Atlas of secular light curves of comets, *Plan. & Sp. Sc* **58**, 365-391. doi: 10.1016/j.pss.2009.09.026.

Giorgini J. D., (2021) JPL/HORIZONS accessed 2021-May-30, computations by Solar System Dynamics Group, Horizons On-Line Ephemeris System, Jet Propulsion Laboratory, Pasadena, USA. Jon. D. Giorgini, author.

Jarrett A. H. and Malcolm G. J., (1987) *An atlas of photographic images of Comet Halley, 1985-1986*, University of the Orange Free State.

Jenniskens P., (2006) in *Meteor Showers and their Parent Comets*, Cambridge University Press.

Jenniskens P., (2020) New Meteor Showers, CBET 4776, IAU Central Bureau for Astronomical Telegrams, D.W.E. Green Ed, May 21, 2020.

Keller H. U., Curdt W., Kramm J. R. and Thomas N. (1994) *Images of the nucleus of Comet Halley.* Volume 1: obtained by the Halley Multicolour Camera (HMC) on board the Giotto spacecraft, European Space Agency, Paris (France), 1994, VI + 252 p., ISBN 92-9092-080-7.

Kronk G. W. In Cometography, https://cometography.com/pcomets/001p.html, accessed June 6, 2021.

McIntosh B. A. and Hajduk A, (1983) Comet Halley meteor stream: a new model *MNRAS*, **205**, 931.

McIntosh B. A. and Jones J. (1988) The Halley comet meteor stream: numerical modelling of its dynamical evolution, *MNRAS*, **235**, 673-293

Merényi E., Földy L., Szegő K., Tóth I. and Kondor A. (1990), The landscape of Comet Halley, *Icarus*, **86**, 9-20.

Ryabova G. O. (2003) The comet Halley meteoroid stream: just one more model, *MNRAS*, **341**, 739-746.

Sato M., (2013) communication posted to the 'meteorobs' mailing list on May 4, 2013.

Whipple F. L., (1987) The Black Heart of Comet Halley, in *Sky and Telescope*, **73**, 242-245.

Yeomans D. K., (1983) in *The Comet Halley Handbook, An Observer's Guide,* 2nd edition, May 15, 1983.

Yeomans D. K., (1986) in *20th ESLAB Symposium on the Exploration of Halley's Comet,* II, 419, ESA SP-250.

# Visiting the SARAO Carnarvon

*IS Glass, SAAO.*

It is not easy to arrange a visit to the SKA site in the Karoo at the best of times and is even more difficult at present due to the Covid-19 epidemic. The last time that I went there was in March 2014 with Maciej Soltynski and the late Tony Foley showed us around (*MNASSA* **73**, 46-51, 2014). On that occasion we drove the 640 km to Carnarvon and stayed over. This time I was fortunate enough to secure a place on the weekly chartered plane flight used by the engineering staff when travelling up from the headquarters in Cape Town. Katryn Rosie, an engineer with SAAO who worked formerly on the HERA project, showed us around. There is now a tarred air strip near the telescopes and the road to Carnarvon has also been tarred, so that access is much easier.

The Engineering and local administrative headquarters are located about 19 km outside town on the farm Klerefontein and the telescopes are 72 km further on at Losberg in the direction of Brandvlei.
We left Cape Town airport at 0730 on 19 May on the Pilatus PC12 turboprop, capable of taking 7 or 8 passengers, and landed at the Observatory about 1½ hours later. We had to switch off our cellphones before arrival and were also not allowed to bring digital cameras on site. The pilot also had to turn off many devices that might cause radio interference. As we came in to land it was thrilling to catch our first glimpses of the MeerKAT telescope dishes off to the side. The airstrip can be seen in Fig 1 to the NE of MeerKAT.


In 2014 construction had been at an early stage. The KAT (Karoo Array Telescope) with 7 dishes was in existence as was PAPER (Precision Array for Probing the Epoch of Re-ionisation). KAT is an experimental array used for testing out designs and training while PAPER has been dismantled after running for several years. Back then, the sites for the 64 MeerKAT dishes had been cleared and marked out and the Karoo Array Processor Building was being fitted with radiofrequency shielding.

*Fig 1. Recent Google Earth view of the site, showing the major installations.*

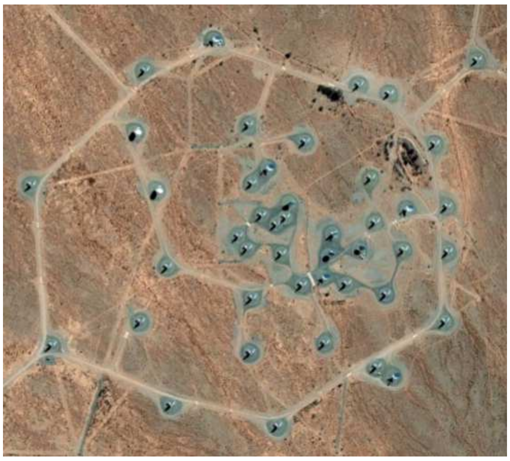

*Fig 2. The central part of the MeerKAT array with about 60% of the dishes within a 1 km diameter circle (Google Earth).*

Now, seven years later, the 64 antennas of MeerKAT are fully operational and quite a few impressive images and quite a few research papers have already come out.

The first receivers installed cover 1.0 to 1.75 GHz (30 cms to 17 cms wavelength – the so-called L-band). Ultimately there will be three interchangeable receivers on each antenna to give coverage from 0.5 to 14.5 GHz (60 cm to 2cm). These are on a turntable so that they can be rotated into the focus position as required. The dishes are 13.5 m diameter and have a combined accuracy (primary and secondary) of 0.6 mm to give about 1/40 wave rms at the shortest wavelengths. The surfaces of the reflectors have a number of small dots to assist in the alignment process.

*Fig 3. A single MeerKAT antenna. The configuration is an offset Gregorian. The radio signals bounce off the big dish onto the smaller one and then into the receiver just below the small one. Two receivers can be seen on the turntable. (Photo: S Burger, Engineering News).*

MeerKAT is a wholly South African project at present but will soon be enhanced by the addition of 20 more antennas provided by the Max Planck Institute for Radio Astronomy. It will also form part of the Square Kilometre Array, an international project, during the next decade. (Wikipedia gives a good summary of the telescope and its programmes.)

HERA, on the other hand, is a collaborative project involving many international institutions.

The HERA (Hydrogen Epoch of Reionization Array) array has taken the place of PAPER and is, of course, much more sensitive. It will soon have 350 fixed dishes of 14m diameter, all but some outlying ones already constructed. It functions as an interferometer, scanning about 440 square degrees of the sky. The signals are fed through fibre optic cables to the Karoo Array Processor Building where they are processed, as are the MeerKAT ones.

Hydrogen radiation has an un-redshifted wavelength of 21 cm and this telescope is designed to observe it when redshifted into the range 600 to 1200 cm, corresponding to z = 6 to 30. HERA's direct aim is to extract the large-scale structure of the primordial inter-galactic medium at different redshifts and provide more understanding of the very early Universe.


*Fig 4. Google image of the HERA array.*

The antennas are of much simpler construction than the MeerKAT ones since they are fixed and operate at much longer wavelengths.

*Fig 5. Side view of the HERA array. The dish surface is constructed of wire birdcage netting and supported by ordinary PVC tubing and fittings.*

The dishes originally focussed the radio waves onto simple dipole antennas to cater for two directions of linear polarisation, but these have been replaced by butterfly-shaped waveguides called "Vivaldi feeds" that offer much better sensitivity over a greater wavelength range than the dipoles.

The heart of the Observatory, where the signals from the individual antennas are combined and turned into images, is the Karoo Array Processor Building, located largely underground and behind an artificial hill formed by the excavated material. It has had to be highly shielded as the computers generate a tremendous amount of radio emission. In the same building are two atomic clocks that are needed to give the precise time reference data needed for combining the signals from the separate antennas to effectively make them into one large dish. On the same site are huge electrical generators to provide uninterruptable power. These are able of generating 4MW, to cater for the SKA, but at the moment the load is about 0.8MW.

The electronic and mechanical workshops needed to service and back up the equipment are located at Klerefontein so that personnel do not go to the antenna area unnecessarily. The figure shows one of the MeerKAT cryostats in the maintenance workshop at Klerefontein.

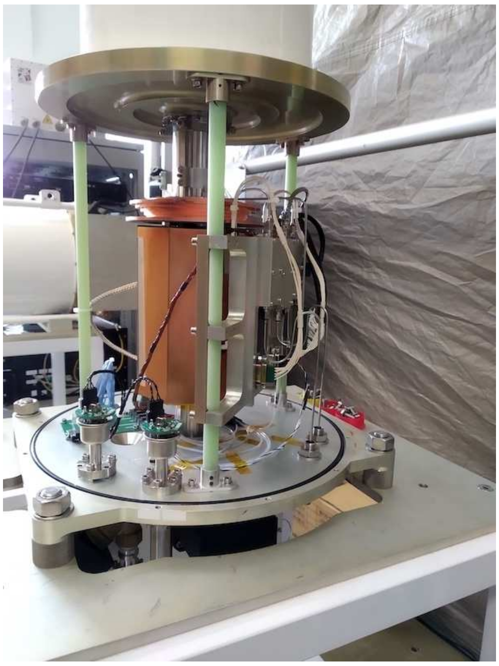

*Fig 6. Each of the three bands on each of the 64 MeerKAT antennas requires a cryostat like this one to contain the critical low-noise part of the detector. On the focal plane turntable of each antenna are three cryostats and the digitising apparatus. High-pressure helium is fed from the telescope mount to power the expansion part of the Gifford-McMahon refrigerator, hidden behind the gold-plated shield in the centre. These were constructed by EMSS Antennas Stellenbosch.*
*(see [www.emssantennas.com](http://www.emssantennas.com) for further details).*

Something that surprised me is that the operations at Carnarvon are entirely centred around engineering. In fact, I did not see any posters or pictures of the spectacular results that MeerKAT has obtained (though I admit that I did not go to every single building in the time available). It is not usually visited by astronomers except on ceremonial occasions! All the controlling of what the telescopes are doing scientifically is done from the Headquarters of SARAO in Observatory, Cape Town.

I would like to thank Kathryn Rosie for arranging my visit and the on-site technicians for patiently explained the various systems.

## Webinars

Colloquia and Seminars form an important part of a research facility, often as a sort of pre-publication discussion or a discussion of an individual's current research, and as such it is virtually impossible to "publish" this material. However, by recording the topics discussed in the form below does indicate to those who are unable to attend, what current trends are and who has visited to do research: it keeps everyone 'in the loop' so to speak

With the advent of CV19, these Colloquia and Seminars are being presented to wider audiences via Zoom and other virtual platforms. The editor has started by identifying what would originally have been "local" Colloquia and Seminars; not easy as there are now Webinars on interesting topics from around the globe! In time we will either return to the traditional Colloquia and Seminars or many will become Hybrid sessions.

Webinar 9 **Title: The cold CGM emerging through trace neutral carbon detections in high-z radio galaxies**

Speaker: Dr. Sthabile Kolwa (University of Johannesburg, South Africa)

Time: 11:00 (SAST) on Thursday 06 May 2021

Abstract: The ionised phase of the circumgalactic medium in high-z galaxies has been widely studied through spectroscopic observations that reveal Ly-alpha emission nebulae surrounding such galaxies. The cold phase of the CGM, however, is rather recently charted territory and within the last decade, there has been burgeoning evidence for existent molecular gas, traced by CO lines, within the CGM of high-z galaxies. In this study, we attempt a search for neutral carbon within seven high-z radio galaxies using the atomic, fine-structure carbon emission line, [CI] 1-0 ($\nu_{rest}$ = 492.161 GHz), observable at the redshifts of $2.9 < z < 4.1$ by ALMA from 80 - 160 GHz. While the survey was expected to be a success, only one of the host galaxies has evidence for narrow-line emission with an approximate line-width of 25 km/s indicative of dynamically cold gas. For the rest of the galaxies, we report 3-sigma upper limits for their line flux and inferred H2 masses. While disappointing, these non-detections may be an indication that the once molecular gas-rich galaxies are now depleted of their H2 supply. This aligns well with previous findings that high-z radio galaxies mostly lie below the Main Sequence of star-forming galaxies and thus have lower SFR than expected for their stellar masses. Our study is therefore both a cautionary tale for those wishing to carry out neutral carbon line-searches at high-z as well as an example of the value in reporting non-detections. There are still many open questions regarding the molecular gas supply of high-z radio galaxies which are and will be important sources for placing observational constraints on radio-mode feedback with MeerKAT and later on, the SKA.

Webinar 10 **Title: The radio galaxy population in the SIMBA simulations**
Speaker: Nicole Thomas (University of Western Cape)
Time: 11:00 (SAST) on Thursday 13 May 2021

Abstract: Essentially all massive galaxies host a supermassive black hole (SMBH) at their center. When these SMBHs become "active" they radiate energy across the electromagnetic spectrum and are identified as Active Galactic Nuclei (AGN). When observed at radio wavelengths, some of these AGN host relativistic jets that span up to hundreds of times the size of the host galaxy. These AGN, otherwise known as radio galaxies, are key contributors to the quenching of star formation in massive galaxies - though the mechanisms driving the accretion and feedback processes of these objects are still poorly understood and defined.

Observations show a dichotomy in the accretion efficiencies of radio galaxies which is thought to be the result of different fuelling mechanisms. With this hypothesis we present results from the SIMBA suite of cosmological simulations that is unique in that
it employs a two-mode sub-resolution prescription for black hole accretion, namely, gravitational torque limited accretion from cold gas, and Bondi accretion from hot gas and accounts for the feedback from active galactic nuclei physically corresponding to observations. We identify a population of radio galaxies in SIMBA and separate them into populations of high and low excitation radio galaxies (HERGs and LERGs), study their global properties, and show that SIMBA provides a state-of-the-art cosmological context for understanding radio galaxies in the era of the Square Kilometre Array.

Webinar 11 **Title: The road from meridian circles to Gaia and beyond**
Speaker: Dr. Erik Høg (Niels Bohr Institute Copenhagen, Denmark)
Time: 11:00 (SAST) on Thursday 20 May 2021

Abstract: The presentation shows how a fundamental and 2000 years old branch of astronomy, the measurement of positions of stars on the sky, astrometry, was revolutionized during the past one hundred years. --This modern development of astrometry began with the application of electronic and digital techniques on the ground at three meridian circle telescopes, at first in Denmark in Copenhagen and at Brorfelde and then in Germany at Hamburg-Bergedorf. The development was continued with space technology in the two large ESA satellites Hipparcos and Gaia launched in respectively 1989 and 2013. Results from Gaia for 1.8 billion stars have been published by 2020 and papers from all branches of astronomy and astrophysics have been published. --The presentation was given on 17 September 2019 in Stuttgart at the annual meeting of the Astronomische Gesellschaft when the instrument

development prize 2019 was awarded to three key persons Lennart Lindegren, Erik Høg, and Michael Perryman.

Webinar 12 **Title: M87: The Ring in Polarised Light**
Speaker: Dr. Iniyan Natarajan (Wits University/SARAO
Time: 11:00 (SAST) on Thursday 27 May 2021

Abstract: The Event Horizon Telescope (EHT) is a global very long baseline interferometry (VLBI) network imaging supermassive black holes at horizon scales at 1.3-mm wavelength. I will present the recently published polarised-light images of the supermassive black hole at the heart of the M87 galaxy. I will discuss how the polarimetric data were analysed and what inferences can be drawn from these results about the magnetic fields near the black hole. Finally, I will consider some open questions and what the future holds for high-resolution black hole observations.

Webinar 12 **Title: Unveiling the unseen magnetized universe with MeerKAT**
Speaker: Dr. James Chibueze, Ass Professor, North-West University, SA.
Time: 10:45 (SAST) on Thursday 10 June 2021

Abstract: Galaxy clusters are known to harbour magnetic fields, the nature of which remains unresolved. Intra-cluster magnetic fields can be observed at the density contact discontinuity formed by cool and dense plasma running into hot ambient plasma, and the discontinuity exists near the second brightest galaxy, MRC0600-399, in the merging galaxy cluster Abell 3376 (redshift 0.0461). Elongated X-ray emission in the east–west direction shows a comet-like structure that reaches the mega-parsec scale . Previous radio observations detected the bent jets from MRC 0600-399, moving in same direction as the sub-cluster, against ram pressure. Here we report radio observations of MRC 0600-399 that have 3.4 and 11 times higher resolution and sensitivity, respectively, than the previous results. In contrast to typical jets, MRC 0600-399 shows a 90-degree bend at the contact discontinuity, and the collimated jets extend over 100 kiloparsecs from the point of the bend. We see diffuse, elongated emission that we name 'double-scythe' structures. The spectral index flattens downstream of the bend point, indicating cosmic-ray re-acceleration. High-resolution numerical simulations reveal that the ordered magnetic field along the discontinuity has an important role in the change of jet direction. The morphology of the double-scythe jets is consistent with the simulations. Our results provide insights into the effect of magnetic fields on the evolution of the member galaxies and intra-cluster medium of galaxy clusters.

Webinar 13 **Title: SALT and TESS monitoring of central stars of planetary nebulae**
Speaker: Ms. Kelebogile Bonokwane (SAAO/UCT)
Time: 11:00 (SAST) on Thursday 17 June 2021

Abstract: Planetary Nebulae (PNe) are the product of Asymptotic Giant Branch (AGB) evolution. Evolved from Solar-like intermediate mass stars (0.8 — 8 M_sun), they have a hot, radiating core that ionizes the gas of the expelled envelope, producing a glowing nebula. Complex, aspherical morphologies are observed in PNe and binary central stars (CSs) have been the favoured explanation for deviations from spherical symmetry. Finding and characterizing the population of binary CSs is thus important to understand the physics behind their morphologies. The objects of this study are Hen3-1333, Hen2-113 and Hen2-47, all with Wolf- Rayet (WR) CSs that commonly exhibit fast, dense stellar winds. All exhibit multipolarity in their young nebulae, Hen3-1333 has a disk and dual-dust chemistry, while the other two have central stars offset from the geometric centre of their nebulae. Here we develop a quantitative time-series analysis to determine whether these objects have binary CSs and develop constraints to permissible orbital parameters.

The High Resolution Spectrograph (HRS) of the Southern African Large Telescope (SALT) was used to collect echelle spectroscopic data over ~3 years and The Exoplanet Survey Satellite (TESS) was used to obtain photometric data for the objects. Using cross-correlation and Gaussian line fitting, radial velocity (RV) time-series were compared to lightcurves determined from the TESS data. Lomb-Scargle periodograms were used to search for periodic variability in the RV and photometry time-series data. The results were discussed based on short (0 — 10 days), intermediate (10 — 1000 days) and long (1000 — 10000 days) orbital period ranges. The quantitative variability analysis excludes short orbital period binary systems, suggesting that if their multiple features are due to binary interactions, the most likely case is the long orbital period range.

## Errata

In the April issue of MNASSA there were two errors. Below are the corrections:

1. Page 51, last paragraph: ‘in a bolide which reached magnitude 23’; that should be magnitude –23
2. Page 60, the caption for Fig. 1 should be: The star might have been a lunar transient phenomenon, LTP, its transience adding symbolism. *Cr. Wikipedia*

The **Astronomical Society of Southern Africa** (ASSA) was formed in 1922 by the amalgamation of the Cape Astronomical Association (founded 1912) and the Johannesburg Astronomical Association (founded 1918). It is a body consisting of both amateur and professional astronomers.
**Publications**: The Society publishes its electronic journal, the *Monthly Notes of the Astronomical Society of Southern Africa (MNASSA)* bi-monthly as well as the annual *Sky Guide Africa South.*
**Membership**: Membership of the Society is open to all. Potential members should consult the Society's web page assa.saao.org.za for details. Joining is possible via one of the local Centres or as a Country Member.
**Local Centres:** Local Centres of the Society exist at Bloemfontein, Cape Town, Durban, Hermanus, Johannesburg, Natal Midlands, Pretoria and Sedgefield district (Garden Route Centre). Membership of any of these Centres automatically confers membership of the Society.
**Sky & Telescope:** Members may subscribe to Sky & Telescope at a significant discount (proof of membership is required). Please contact the Membership Secretary for details.
**Internet contact details:** email: assa@saao.ac.za Home Page: http://assa.saao.ac.za

| Council Members 2020 | | |
|---|---|---|
| President | Chris Stewart | mwgringa@mweb.co.za |
| Vice-President | Case Rijsdijk | particles@mweb.co. |
| Membership Secretary | Wilmi Nel | assa@ipsissimaverba.co.za |
| Treasurer | AJ Nel | assa@ajnel.co.za |
| Secretary | Lerika Cross | lerika@icon.co.za |
| Scholarships | Dr Claire Flanagan | Claireflan55@gmail.com |
| Members | Clyde Foster | clyde@icon.co.za |
| | Dr Peter Kotze | pkotze@sansa.org.za |
| | Dr Ian Glass | glass.ian@gmail.com |
| Bloemfontein Chair | Thinus van der Merwe | Mjvdmerwe@ufs.ac.za |
| Cape Chair | Marius Reitz | ReitzM@gmail.com |
| Durban Chair | Piet Strauss | pstrauss@marine-images.co.za |
| Garden Route Chair | Case Rijsdijk | particles@mweb.co.za |
| Hermanus Chair | Dr Pierre de Villiers | pierredev@hermanus.co.za |
| Johannesburg Chair | Carmel Ives | Carmel.t.ives@outlook.com |
| Midlands Chair | Steffan Devos | sdevos@webbis.co.za |
| Pretoria Chair | Bosman Olivier | Bosman.olivier@gmail.com |
| Section Directors | | |
| A - Shallow Sky | Clyde Foster | clyde@icon.co.za |
| B1 - Deep Sky<br>B2 – Double and Variable Stars | Douglas Bullis<br>Dave Blane | douglasbullis@gmail.com<br>theblanes@telkomsa.net |
| C - Photometry, Spectroscopy | Percy Jacobs | percymj@iafrica.com |
| D - Cosmology/Astrophysics | Bruce Dickson | noisejammer@gmail.com |
| E - History | Chris de Coning | Siriusa@absamail.co.za |
| F - Dark Sky | Vacant | |
| G - Imaging | Martin Heigan | mheigan@icon.co.za |
| H – Instrumentation and ATM | Chris Stewart | mwgringa@mweb.co.za |
| I – Citizen Science | Allen Versfeld | Allan.versfeld@gmail.com |

ISSN 0024-8266

# mnassa

monthly notes of the astronomical society of southern africa

Volume 80 Nos 5-6 June 2021

## CONTENTS