The Brightness Behaviour of Comet C/2006 P1 McNaught

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The public reaction to the bright comet C/2006 P1 McNaught was adequately covered in *MNASSA* (Koorts 2007). Therefore rather than go over similar material again, this article addresses questions that were asked of me concerning the brightness of this comet.

Predicted brightness of comet McNaught

Comets are notoriously unpredictable when it comes to how bright they will appear. Consider for example comet C/1973 E1 Kohoutek, predicted to reach magnitude –5 or brighter, and be visible in broad daylight, or even comet 1P Halley which disappointed most of the public after it had been hyped up before its 1986 apparition. Comet C/2006 P1 on the other hand clearly became brighter than originally predicted. As a first approximation (see for example Cooper and Begbie 2004) the brightness of a comet can be predicted from the equation:

$$m1 = H_0 + 5 \log \Delta + 2.5n \log r + \varphi \qquad (1)$$

where m1 = total cometary magnitude
H_0 = absolute magnitude of comet at $\Delta = r = 1$ au
Δ = geocentric distance of comet in au
r = heliocentric distance of comet in au
φ = correction for phase angle

Thus comet McNaught was predicted to reach perhaps magnitude –2 near perihelion on 2007 January 12 (assuming $H_0 = 6$ and $n = 4$) but with perihelion distance of $q = 0.17$ au and elongation of <5° from the Sun it was not expected to be visible at its brightest. In the event most observers seem to agree it peaked at magnitude ~ m1 = -5 to -6, or about 15-40 times brighter than predicted. In the days after perihelion passage the comet was visible low after sunset only slightly fainter than nearby Venus, then at magnitude –3.9. In order to understand why it was brighter than predicted it will be useful to understand the nature of comets and how they behave as they travel through the inner solar system.

The varying nature of comets and factors affecting their brightness

Comets were formed from the residual matter left over from the formation of the solar system, and as such comprise the dust, frozen ices and gases which failed to coalesce into the Sun and planets. The type of dust, ices and gases and the ratio of dust to volatiles varies from comet to comet depending on where they formed in the primordial solar nebula, the conditions under which they formed and the conditions they were exposed to in the 4.5 billion years since formation.

Cometary dust would appear to be of two types; dust containing light elements referred to as CHON after its mainly organic composition, and metallic silicates largely of Ca, Mg and Fe. These silicates are present as both amorphous (glassy) and crystalline olivines and pyroxenes. CHON particles are present as refractory organic grains and are probably much less reflective than the silicates. Thus a comet rich in silicates will likely have a larger albedo (reflectivity) and appear brighter than one where CHON predominates. The brightness is also affected by the phase angle, which is the angle subtended by the earth and Sun as seen from the vantage point of the comet. For example Gehrz and Ney (1992) studied the infra red brightness of several comets, and found a three times mean increase in their albedos when moving from a phase angle of 50° to 150°.

Brightness also depends on the sizes and shapes of the dust grains. The dust grains are mainly non-spherical and consist of aggregates rather than individual particles. There is a wide range of individual particle and aggregate sizes, from sub-micron to a centimetre or larger. "Scattering" is said to occur when sunlight changes direction due to interaction with particles and larger molecules in the coma and tail. Scattering is called Rayleigh type when caused by very small (sub-nanometre) particles and molecules, Mie type when due to particles of similar diameter to the light wavelength (400-700nm in the visible region) and non-selective when larger grains are involved. Hence brightness depends critically on the particle size distribution within the coma or tail.

The main volatile constituents of cometary nuclei are carbon monoxide, carbon dioxide and water vapour. Varying amounts of other volatiles may be present, such as methane, ammonia, hydrogen cyanide, hydrogen sulphide, methanol, formaldehyde, and more exotic organic molecules. As the comet approaches the Sun from its frozen state, carbon monoxide is the first major component to sublimate and is the primary driver of a comet's brightness. As the comet nears the Sun, carbon dioxide sublimates, followed by water ice, to form water vapour. As these constituents volatilize they congregate to form the coma, at the same time releasing dust grains from the nucleus and increasing the brightness due to the scattering of the growing number of particles in the coma. H_2O forms the largest fraction of cometary ice (Bockelée-Morvan et al 2004). CO is next most abundant but the ratio of H_2O to CO may vary considerably from comet to comet. The relative abundance of the different volatiles and the temperature at which they 'switch on' (relative to the distance from the Sun, r) may have a profound effect on the brightness development and activity in the solar vicinity.

Molecules from the sublimation of frozen gases also are ionised or excited in the presence of energetic sunlight, and may emit light at visible wavelengths as a result. Parent molecules may in turn be dissociated into daughter species which undergo similar fluorescence. Thus species such as C_2 and CO^+ emit light at visible wavelengths, and are responsible for the characteristic greenish-blue colour of some comets. The overall colour and brightness at different wavelengths depends on the inventory of different emitting species and on the level of energetic solar radiation.

The activity of the comet also depends on its structure. So for example a comet arriving from the Oort Cloud for the first time may have a tenacious surface crust which is difficult to melt, compared to a returning one whose surface has already been modified by previous sublimation episodes. Some cometary nuclei may be well compacted and thus able to survive many apparitions, while others may be tenuous and of low tensile strength. Disintegration episodes may be accompanied by rather large and sudden increases in brightness, while jets emanating from fissures on the surface may cause periodic brightness variations as they rotate in and out of sunlight.

Thus comets shine due to both light scattering by particles and larger molecules, as well by fluorescence of atoms and molecules emanating from its volatile components, excited by solar radiation. In relation to Equation 1, we can see the first factor determining the brightness of a comet is its absolute magnitude, H_0. Intrinsically bright comets have $H_0 \sim 0$ (Comet C/1995 O1 Hale-Bopp had $H_0 = -0.5$), and the average comet >5 (the mean of the 7 comets studied in Cooper and Begbie 2004 was $H_0 = 6.2$). This parameter is affected by the size of the object, larger objects having generally higher intrinsic brightness, its albedo, the dust to gas ratio, the composition of the dust in the nucleus and the particle size and shape of the dust grains, as well as the phase angle.

The next factors affecting the brightness of the comet are its distances from the earth (Δ) and Sun (r). Thus comet C/1996 B2 Hyakutake, while not an intrinsically bright comet with $H_0 = 5.2$, reached magnitude 0 in March 1996 due to a close approach to earth of less than 0.1 AU. Similarly a close approach to the Sun, as in the case of the subject comet with r = 0.17 AU reduces the contribution of the term 2.5n(log r) and may result in a bright comet when near to the Sun.

The last variable in the brightness equation is n, also called the photometric constant, which is the rate at which the comet brightens or fades relative to its distance from the Sun (r). The value may differ pre and post perihelion and from apparition to apparition for a single comet, but typical long period comets have $n<4$ and short period comets have $n>5$. The value of n is influenced by the sublimation rates of volatiles from the nucleus, which are in turn dependent on the gas/dust ratio, the ratio of different volatiles, especially H_2O, CO and CO_2, and the structure of the nucleus, especially its surface strength and aspect. Comet C/1995 O1 Hale-Bopp showed a distinct difference in brightening behaviour in its pre-perihelion arcs, with n = 3.9 for r = 7.1-4.8 followed by n = 3.0 for r = 4.8-2.1. This difference was attributed to the late volatilisation of H_2O, taking over from CO as the primary brightness driver.

Actual Brightness Behaviour

It must be stressed that equation 1 represents only the average brightness prediction of a comet. The observed brightness performance of comet C/2006 P1 is shown in Figure 1. It is based on observations collected by Jon Shanklin (2007) and includes ASSA observations. While the comet was well observed from South Africa, most observations were too empirical to be of scientific use, and hence the only observations included in the analysis were those conforming to ICQ report format, including those of Magda Streicher, Koos van Zyl, Theo Smith and the author. In any case these were the only observers to continually follow the comet after it faded below first magnitude!

The date of perihelion was January 12.8, and the date of closest approach to earth was three days later on January 15.5 with Δ = 0.817 AU. The light curve shows few observations pre-perihelion before the end of 2006. Northern hemisphere observers were first to realise the comet was becoming brighter than predicted and successfully observed the comet as it neared perihelion. The author issued a request to ASSA observers by way of an extraordinary circular on January 10. The first ASSA observer to locate the comet was Mauritz Geyser on January 12, who saw it in broad daylight with 7x42 binoculars, after taking special precautions to block out the light from

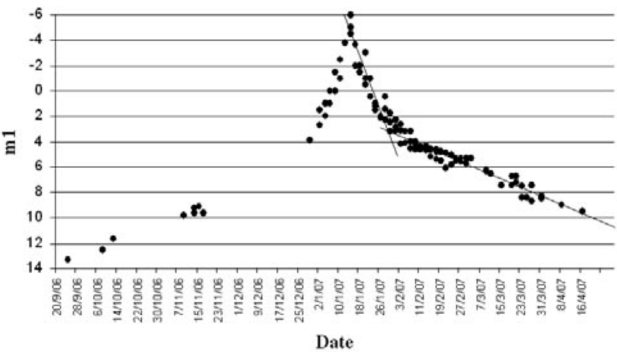

Fig. 1 Light-curve of Comet C/2006 P1 McNaught

the nearby Sun. The light curve shows a peak brightness of m1 = -6 just after perihelion, followed by a rapid fading to magnitude 3 by end January 2007, and a more gradual fade thereafter corresponding to a distance of r > 0.6 au. It was below naked eye visibility by the end of February 2007. From the same light curve data I derived the following equations based on the plots in Figure 2 (solid circles pre-perihelion, open circles post perihelion):

Overall	m1	$= 4.8 + 5 \log \Delta + 11.0 \log r$	(2)
Pre perihelion	m1	$= 5.9 + 5 \log \Delta + 11.7 \log r$	(3)
Post perihelion	m1	$= 4.2 + 5 \log \Delta + 10.0 \log r$	(4)

The data derived from these equations may be summarised as follows:

	H_0	n
Overall apparition	4.8	4.4
Pre perihelion	5.9	4.7
Post perihelion	4.2	4.1
Post r <0.6		4.9
Post r >0.6		4.0

The intrinsic brightness thus appears higher post perihelion. Closer analysis of the post perihelion behaviour shows a fade according to n = 4.9 up to r = 0.6, after which it faded more slowly with n = 4.0.

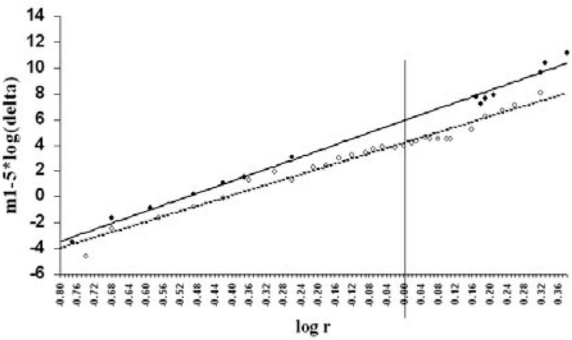

Fig. 2 Brightness behaviour, Comet C/2006 P1

Conclusion

Considering the value of H_0 = 4.8 the comet was intrinsically perhaps only a little brighter than the average comet making its first visit from the Oort Cloud. Also with n around 4-5, the rate of brightening and fading is at about the upper limit expected for a first time long period comet. There is no evidence of any fragmentation of the nucleus either in the light curve or visually despite reports from one observer who photographed the comet. The latter was probably due to an artifact in the image.

Thus I conclude comet C/2006 P1 was neither an intrinsically bright comet, nor was there any exceptional rate in its brightening or fading. Its prominence was probably due a high dust content of very reflective silicate dust, made more abundant due to intense sublimation of volatiles after a close approach to the Sun of only 0.17 au at perihelion, and coupled with a favourable viewing geometry just after perihelion. The high dust content in turn contributed to a rather prominent tail which added to the overall spectacle of the comet.

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Cosmology in the Trenches:

Snapshots from the Quest for the Age of the Universe and the Cosmic Distance Scale

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Based on the presentation given by Dr Dave Laney, exiting ASSA president, at the 2007 AGM, held at SAAO Cape Town on 25 July 2007.

> Whenever you approach the human race,
> there's layers and layers of nonsense.
>
> Thornton Wilder

> Beauty is truth, truth beauty, -- that is all
> Ye know on earth and all ye need to know.
>
> Keats

A common assumption today is that there is really nothing more to say about the age of the universe or the cosmic distance scale. After all, the Wilkinson Microwave Anisotropy Probe (WMAP) has spoken and everything is now known to incredible accuracy. Working from WMAP and other observations of the very small variations across the sky in the intensity/ 'temperature' of the cosmic microwave background radiation, which is thought to preserve a record of fluctuations in the universe as it was 380 000 years after the beginning, cosmologists quickly deduced the 'final' answers (Spergel et al. 2003, Bennett et al. 2003):

Age of the universe: 13.7±0.2 billion years

Hubble constant (h_0): 0.72±0.05