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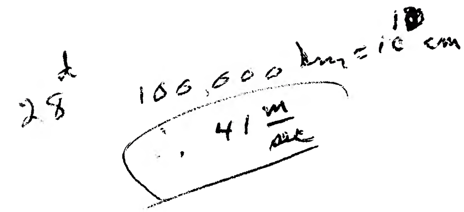
Comet Halley's outburst



David W. Hughes
Department of Physics, University of Sheffield, Sheffield S3 7RH

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SUMMARY

It is suggested that the outburst suffered by Comet Halley (1986 III) in early 1991 February, was caused by the ejection from the nucleus of 1.4×10^{13} g of dust, this being about 0.02 per cent of the cometary mass. The energy required was in the range 2×10^{19} to 2×10^{23} erg. The most likely source of this energy was an impact with a member of an outer asteroid belt, the impacting object having a diameter of between about 2.6 and 60 m.

1 INTRODUCTION

On 1991 February 12, Hainaut & Smette (1991) were observing Comet Halley (1986 III) using the Danish 1.54-m telescope at the La Silla Observatory, Chile, as part of the European Southern Observatory monitoring programme. Instead of seeing the expected coma-free dirty-snowball nucleus of apparent magnitude, m_1, about 25.3, they detected an extended nebula that was almost 300 times brighter than recent light-curve extrapolations had predicted (see *IAU Circ. No. 5189*). The nebula cloud, of m_1 about 19, extended over an area greater than 20 arcsec on the sky (projected diameter 200000 km) and no obvious changes were seen over a 3-d period. The outburst was confirmed by K. J. Meech (*IAU Circ. No. 5196*) using CCD observations taken with the University of Hawaii's 2.2-m telescope and by Buil *et al.* (1991) using the 0.61-m telescope of the Pic du Midi Observatory. Giraud & Smette (1991) noted that the spectrum mirrored the solar spectrum (the outburst having a $V–R = +0.59$) indicating that dust scattering was the responsible agent. West (1991) observed the comet on seven consecutive nights (1991 March 12.2–18.2) and found that the overall size of the coma was then greater than 30 arcsec. Morphological changes were seen from night to night.

During 1991 February and March Comet Halley was 14.3 AU from the Sun and moving away with a velocity of 8.7 km s^{-1}. The cometary nucleus had a surface temperature of about 70 K.

Comet Halley is the only comet to be seen to have an outburst at such a great heliocentric distance. Four possible causes have been suggested (see Hainaut & Smette 1991):

(1) a cratering event caused by the comet colliding with a small asteroid-like body;

(2) an explosion caused by the release of a large amount of energy stored in the nucleus;

(3) dust ejected through fissures in the nucleus surface due to internal restructuring triggered by thermal waves in the cooling comet; and

(4) dust electrostatically elevated from the nucleus surface due to an interaction with highly energetic solar wind particles.

All of these result in the formation of a temporary dust cloud around the nucleus. Calculations to be given later in this short communication show that the mass of dust required to produce the observed increase in scattering cross-section is around 1.4×10^{13} g. The energy needed to eject this dust is in the range 2×10^{19} to 2×10^{23} erg.

It is suggested in this communication that the most probable source of this energy is an impacting small asteroidal body of diameter between about 2.6 and 60 m. The other possibilities are much less likely because first the porous, low-density cometary nucleus has no obvious means of storing energy, secondly the restructuring is unlikely to take place at a time when the thermal gradients are near their minimum values and thirdly the nucleus has an insufficient cross-section to absorb a significant amount of energy from the solar wind.

2 THE DUST COMA

Images taken by the camera on board the *GIOTTO* spacecraft in 1986 March indicated that the nucleus of Comet Halley had typical dimensions of $8.2\times8.5\times16$ km and a surface area of 400 km^2 (see Keller *et al.* 1987). The quiescent nucleus would thus expose a mean cross-sectional area of 100 km^2 to the solar radiation flux. A 300-fold increase in brightness could be obtained by ejecting dust from the cometary nucleus in such quantities that (assuming that the dust cloud is optically thin) the total scattering area increased by a factor of 300.

Using observations of many meteoroid streams Hughes (1978a) found that the dust ejected from a cometary nucleus had a mass distribution index that was 1.71 for particles with masses less than 10^{-1} g and 2.27 for masses greater than that value. Following Hughes (1972), the mass distribution index, s, can be defined such that the number of objects in the mass interval m to $m+dm$ is $N(m)dm$ where $N(m)$ is proportional to m^{-s}. An example of the mass distribution of cometary dust is given in Table 1 (see Hughes 1978a). This distribution has been 'normalized' such that the mass in the 10^{-2} to 10^0 g interval is 10^{14} g. The density values used in this table are also justified in, and taken from, Hughes (1978a).

Particles that are smaller than a few μm are ineffective scatterers of visible light, so it is only the dust particles that are more massive than about 10^{-10} g that scatter light from the vicinity of the comet. Summing all the masses in the second column of Table 1 and the total cross-sectional area of the particles more massive than 10^{-10} g leads to the conclusion that 1.76×10^{14} g of emitted cometary dust would have an equivalent scattering area of 3.8×10^{15} cm^2.

The 300-fold brightness increase seen for Comet Halley requires a dust area of 3×10^{14} cm^2 and scaling the figures given above indicates that this could be produced by the comet ejecting about 1.4×10^{13} g of dust. McDonnell *et al.* (1987) found that the ratio between the mass of dust and the mass of snow per unit volume of the nucleus of Comet Halley was about 1.0. It can thus be concluded that the outburst dust coma was produced by the comet losing a total mass of twice the above value, i.e. 2.8×10^{13} g. Rickman (1986) estimated that the density of the nucleus of Comet Halley was 0.2 g cm^{-2}, thus giving the comet a total mass of 1.5×10^{17} g. An ejection of only 0.02 per cent of this mass was required for the cloud. [It might be worth noting that in its recent history P/Halley has typically lost about 0.08 per cent of its mass at each apparition, see Hughes (1985).]

In the cometary nucleus the dust is probably enmeshed in a fragile low-density bird's-nest matrix of snow. An upper limit to the energy required to release and eject the dust can be obtained by calculating the energy required to sublimate an equal mass of snow. Here it is suggested that it is the gas resulting from this sublimation that will push the dust away from the comet by momentum transfer. Note that a typical cometary outburst (see Hughes 1990) has a duration of 20 to 30 d. This range is dependent on the velocity of the ejected gas and dust with respect to the cometary nucleus and on the rate of input of new material from the outburst site. Due to these factors the observed outburst duration is expected to increase as a function of heliocentric distance. The duration of the outburst of P/Halley will also be increased considerably due to the fact the Earth-bound observer is observing *along* the direction in which the comet is moving. The dust has been emitted from the comet with a low cometo-

Table 1. An example of the mass distribution of cometary dust.

Mass interval (g)		Total mass in interval (g)	Number of particles in interval	density of particle (g cm^{-3})	Total X-section area of particles in interval (cm^3)
10^{4}	10^{6}	2.4×10^{12}	2.4×10^{7}	0.3	1.4×10^{11}
10^{2}	10^{4}	8.3×10^{12}	8.3×10^{9}	0.3	2.2×10^{12}
10^{0}	10^{2}	2.9×10^{13}	2.9×10^{12}	0.3	3.6×10^{13}
10^{-2}	10^{0}	1.0×10^{14}	1.0×10^{15}	0.3	5.8×10^{14}
10^{-4}	10^{-2}	2.6×10^{13}	2.6×10^{16}	0.8	3.7×10^{14}
10^{-6}	10^{-2}	6.9×10^{12}	6.9×10^{17}	0.8	4.5×10^{14}
10^{-8}	10^{-6}	1.8×10^{12}	1.8×10^{19}	3.5	1.1×10^{15}
10^{-10}	10^{-8}	4.8×10^{11}	4.8×10^{20}	3.5	1.3×10^{15}
10^{-12}	10^{-8}	1.3×10^{11}	1.3×10^{22}	3.5	1.6×10^{15}
10^{-14}	10^{-12}	3.3×10^{10}	3.3×10^{23}	3.5	1.9×10^{15}

centric velocity. The vectoral addition of this velocity to the much larger orbital velocity of the parent comet shows that the dust will move off on orbits that are very similar to that of the comet. The dust will occupy a cylindrical volume of space with the long axis of the cylinder along the comet's orbit. As time passes the cylinder will increase in length. But as the dust is optically thin an observer looking along the axis of the cylinder (as the Earth-bound observer does) will see very little change in the intensity of the scattered light as a function of time.

Whipple (1972) concluded that the sublimation energy required to convert the snow in the cold cometary nucleus into gas at the nucleus surface was of the order of 1.26×10^{10} erg g^{-1}. So the 1.4×10^{13} g of snow lost by the comet during the outburst requires a sublimation energy input of 1.74×10^{23} erg. Some of the released energy will also go to heating the gas and accelerating the dust away from the nucleus. As the escape velocity from the surface of the nucleus is only 2 m s^{-1}, against the mean H_2O gas velocity of 420 m s^{-1}, little additional energy is required and we can assume that the upper limit to the total energy needed for the production of the dust cloud is around 2×10^{23} erg.

A lower limit is estimated by noting that the energy of the impacting object might only be needed to both break the bonds of the fragile dust–snow matrix and accelerate the dust–snow fragments to a velocity above the escape velocity. Indeed there is evidence from the recent observations of Comet Halley (see for example Brownlee & Kissel 1990) that just such CHON grains were being produced in profusion from the comet when it was close to perihelion. The energy required to accelerate a mass of 2.8×10^{13} g to twice the cometary escape velocity is about 2×10^{18} erg. The lower limit to the total energy required to produce the outburst is obtained by increasing this value to take into account the energy required to break up the dust–snow matrix but we still arrive at an energy value some 10^4 lower than the upper limit.

3 ASTEROIDAL IMPACT

The most probable source of the required energy is the kinetic energy of an incident asteroid. The velocity of this asteroid is not known but estimates can be made. If it were in a circular orbit of radius 14.3 AU it would have a heliocentic velocity of around 8 km s^{-1}. At the same distance Comet Halley has a velocity of 8.7 km s^{-1} and is moving almost directly away from the Sun. The interception velocity between the asteroid and the comet is thus about 11.8 km s^{-1}. To provide the upper limit energy mentioned above, the asteroid would have to have a mass of 2.9×10^{11} g. An assumed density of 3 g cm^{-3} gives the asteroid a diameter of 5700 cm. The lower limit energy requires an asteroid of diameter about 260 cm.

Zellner & Bowell (1977) found that

$$2 \log (D/2) = 5.642 - 0.4\ V(1, 0) - \log p_v,$$

where D is the mean diameter of the asteroid in km, $V(1, 0)$ is the opposition absolute visual magnitude and p_v is the geometric albedo. If we assume that both the large and small impacting asteroids have an albedo of 0.06, the apparent magnitudes at an opposition distance of 13.3 AU will be 30.5 and 37.2 respectively.

What sort of crater would the impact make? Unfortunately the vast majority of the observed craters in the solar system have been formed in the surfaces of solid rocky bodies. The cometary nucleus is a low-density porous fragile structure in which shock waves will travel with great difficulty. The comet crater will tend to resemble a cylindrical pit. The volume can be estimated by noting that 1.4×10^{13} g of snow at a partial density of 0.1 g cm^{-3} occupies 1.4×10^{14} cm^3.

Dence, Grieve & Robertson (1977) estimated that, for solid rocky bodies such as Moon and Earth,

$$E = 1.01 \times 10^{23}\ D_c^{3.4} \text{ erg},$$

where E is the kinetic energy of the impacting object and D_c km is the diameter of the resulting crater. This equation indicates that the ratio between the crater diameter and the diameter of the incident asteroid is about 20. The comet, however, has a density that is about 1/18 that of the Moon and thus the ratio is expected to decrease to around 5. In the upper limit case the comet crater would thus have a depth of 2.2 km. This later figure is equivalent to 20 per cent of the mean diameter of the comet. We can speculate that some remnant of the incident asteroid might be resting at the bottom of the crater pit. Note that larger impacting asteroids might even pass right through the nucleus.

The outburst took place when the comet was about midway between Saturn and Uranus. Do asteroids exist in this region of the solar system? And if they do, do they have a physical form similar to those in the inner asteroid belt or do they contain ice and thus have a structure more similar to cometary nuclei? There is no obvious cosmogonic objection to either of these suggestions, in fact a very large member of this group, 2060 Chiron, was discovered in 1977 October. Chiron has a highly elliptical orbit of semimajor axis 13.6 AU, eccentricity 0.38 and inclination 6.9°, that takes it 1 AU inside the orbit of Saturn and to within 2 AU units of Uranus (see for example French *et al.* 1989). It also has an estimated diameter in the range 50 to 300 km (see Hughes 1978b) and has been found to have comet-like features. Smaller asteroid–comets in the Chiron group would be very faint, and would also have low celestial angular velocities. Both these factors mitigate against detection and there are no astronomical searches taking place at the present for these objects. The asteroids 1991 DA and 944 Hidalgo are the only other known members of this group (Anderson 1991).

The processes responsible for the origin of the solar system produced an asteroid belt between Mars and Jupiter. Other belts could have been produced in the larger volumes of space between Jupiter and Saturn, Saturn and Neptune and Neptune and Uranus. There is also every possibility that the asteroids in these outer regions have different compositions to those in the inner belt. The lower temperatures would have led to the production of dust–snow planetesimals indistinguishable from the cometary nuclei that enter the inner solar system. Also, as the rate of accretion decreased as a function of heliocentric distance (see Hoyle 1978), the maximum size of asteroids in these outer belts is probably considerably lower than that in the Mars–Jupiter belt.

It is worth noting that an alternative way of searching for asteroids that venture into the trans-Saturnian regions is to keep a close watch on the nucleus of a large comet as it retreats through that region. This is only being done for the famous Comet Halley. On 1991 February 12 this comet hit a trans-Saturnian asteroid of diameter between 57 and 2.6 m and the fourth of these asteroids to be discovered was quickly destroyed. Note that in a well-fragmented outer asteroid–comet belt a 2.6-m diameter object would be 10 000 times more common than a 60-m object.

4 CONCLUSION

Cometary outbursts are common and a host of phenomena have been suggested as possible causes (see Hughes 1990 for a review). Unfortunately the vast majority of these phenomena become less efficient as the cometary heliocentric distance increases. The collision hypothesis is the only one that does not. At a comet–Sun distance of 14.3 AU an impact between Comet Halley and a minor member of an outer asteroid belt is by far the most likely explanation for the 300-fold increase in brightness. Extended observations of Comet Halley must be carried out to establish just how rare these outer asteroids are.

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