THE BREAKUP OF C/1999 S4 (LINEAR), DAYS 0–10

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Abstract. The evolution of the morphology of C/1999 S4 (LINEAR) is examined from a series of images taken from shortly before the disruption of the nucleus until 10 days afterwards. This is combined with light curve data to provide a unique documentation of the early evolution of the disruption event. Neither images from the 1-m Jacobus Kapteyn Telescope nor the 2.5-m Isaac Newton Telescope at the Roque de los Muchachos Observatory (La Palma, Canary Islands, Spain) show no evidence of bright sub-nuclei, although the presence of a well-defined stable lance-point structure in the head of the comet indicates that a dust and gas producing source remained active in this region. The centre of brightness of the coma moved in the anti-solar direction at a few tens of metres per second after disruption indicating that it was a mainly dust structure. The contrast in the fragmentation history of comets such as C/1999 S4, C/2001 A2 and 141P/Machholz 2 suggests that there is a wide variation in nucleus properties from highly unstable and loosely bound rubble piles to relatively consolidated conglomerates.

Keywords: C/1999 S4 (LINEAR), comets, nucleus splitting

1. Introduction

C/1999 S4 (LINEAR) was discovered on 1999 September 27 at a distance of r = 4.27AU. Given its brightness at discovery and relatively small perihelion distance significant interest was generated in this object because of the possibility that it would become naked-eye visible some 10 months after discovery, allowing significant preparation of observations.

The comet was dynamically new in the Oort Cloud sense with $1/a = +0.000024 \pm 0.000001$ against the "typical" value for an Oort Cloud comet of $1/a = +0.000040$ (Marsden, private communication). Such comets are generally rich in volatiles and follow a rather large power law brightening rate before water switch-on at around 3AU. The brightening rate of C/1999 S4 was though similar to somewhat evolved objects such as C/1995 O1 (Hale–Bopp), rather than to dynamically new objects such as C/1989 (Austin) or C/1973 E1 (Kohoutek) that may follow a 5th or 6th power law initially. Another somewhat anomalous feature of C/1999 S4 was the unusually large non-gravitational parameters (see Table I).

Note though that Weaver (2000), Weaver et al. (2001) reported that the comet was strongly depleted in low temperature volatiles such as CO compared to dynamically "fairly" new comets such as C/1996 B2 (Hyakutake) of C/1995 O1 (Hale–Bopp). Such a situation is somewhat unusual given that dynamically new

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TABLE I

Non-gravitational terms and light curve brightening for C/1999 S4 and three recent, bright comets. Note the unusual size of the parameters for C/1999 S4 despite the lack of any observed jet activity. The brightening rate was typical of a dynamically evolved object rather than a new one in the Oort Cloud sense

Comet	A1	A2	Brightening	References for A1 and A2
C/1995 O1	1.27	0.1144	$m \propto 10.0 \log r$	(Marsden, 2001)
C/1996 B2	2.56	0.0485	$m \propto 8.7 \log r$	(http://www.aerith.net/comet/catalog/1996B2/1996B2.html)
C/1999 S4	9.50	−2.11	$m \propto 8.0 \log r$	(Marsden, 2002)
C/2001 A2	0.47	−0.3558	$m \propto 7.5 \log r$	(Marsden, 2001)

objects are usually found to be richer in low-temperature volatiles than more evolved objects. (Mumma et al., 2001) suggest that the explanation for this depletion is that the comet was formed at a much lower heliocentric distance (~5-10AU) than for other comets such as 1P/Halley, C/1995 O1 (Hale–Bopp) and C/1996 B2 (Hyakutake) that are thought to have formed at >20AU from the Sun.

2. Fragmentation History

Weaver (2000) reported a factor of 7 variation in flux in 2.2 days in observations with the Hubble Space Telescope, coincident with the observation of the separation of a small fragment on 2000 July 5–7. The aperture used was 0.15 arcsec, equivalent to 93 km at the comet. Observations taken on 2000 June 28th and July 1st suggest that there was an important colour and morphological change in the comet's inner coma between the two nights (Schulz and Stüwe, 2002). Schleicher (2000) also found evidence of significant variability in 1999 December.

Figure 1 shows CCD monitoring of the inner coma of C/1999 S4 (LINEAR) in late February and early March 1999 by Spanish amateur astronomers (see Kidger, 2002; Kidger and Manteca, 2002 for details of the observational method used). We see strong evidence of a major outburst in the light curve with an amplitude of 1 magnitude and a rise time of a few days. After maximum the flux returned to close to pre-outburst level in ~48 h. At Δ=3.01 AU, the physical radius of the aperture was 11 000 km at the comet and thus the decay time only implies velocities within the aperture of ~60 m/s. We suggest that this event has the signature of a minor fragmentation event similar to, but probably larger than that observed by Weaver (2000). There was a similar, bit less well observed event in late January 2001. Such events and their repeated occurrence in the light curve suggest that the comet was probably splitting off small fragments constantly during practically all its inbound

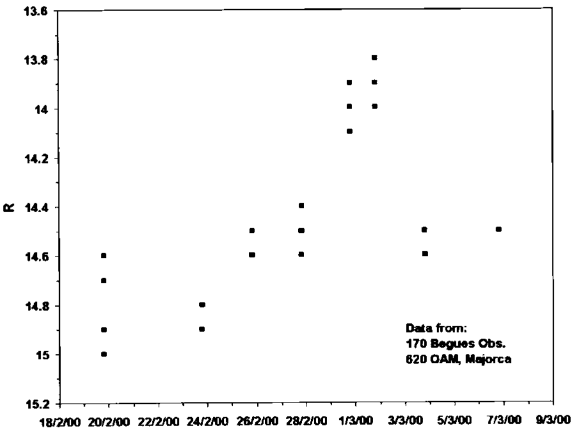

Figure 1. The light curve of C/1999 S4 (LINEAR) taken from Spanish CCD data between 2000 February 18 and March 06. Clear evidence is seen of a major outburst with an amplitude of ≈1 magnitude.

leg. This is consistent with the observation of 4 major outbursts by the SWAN camera of SOHO between late May and August 2001 (Mäkinen et al., 2000).

3. Outburst to Disintegration

Systematic observation of C/1999 S4 (LINEAR) through its perihelion passage was carried out with the 1-m Jacobus Kapteyn Telescope (JKT) and 2.5-m Isaac Newton Telescope (INT) at the Roque de los Muchachos Observatory (La Palma, Canary Islands, Spain). Observations were carried out in photometric conditions on 2001 July 23, 24, 25, 26, 27, 28 and 30 (no observations were possible on the 29th due to the evacuation of the observatory caused by a nearby severe forest fire) with the JKT and on 2001 Jul 31 and Aug. 1 with the INT. The JKT used the standard Cassegrain CCD camera with a field of 11 arcmin and the INT the Wide Field Camera with a field of half a degree. Standard UBVRIZ filters were used. Details of the filters and photometric system are given in González-Pérez et al. (2001).

The comet was in outburst on 2001 July 23.9 with a well-defined plasma tail (Figure 2). The surface brightness of both coma and tail was sharply reduced in July 24.9; despite increasing the exposure from 2 to 10 s the size of the coma is greatly reduced and the tail has almost disappeared (Figure 3). On July 25.9 the first images were taken in strong twilight. It was at once evident that the comet had suffered a severe disruption: the inner coma was strongly elongated in a manner reminiscent of the early post-discovery images of D/1993 F1 (Shoemaker–Levy 9) and its brightness had suffered a further sharp decline. On successive nights the surface brightness continued to decrease rapidly.

Figure 6 shows the decline in the surface brightness of the inner coma which, on nights from July 25.9 onwards drifted away from the nominal position of the

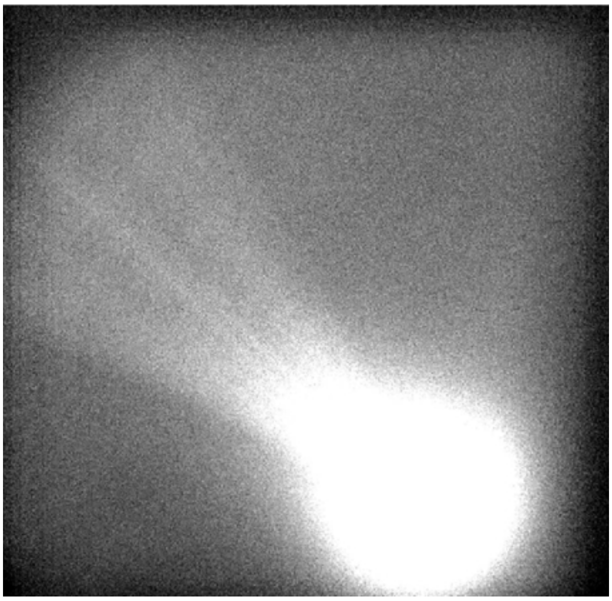

Figure 2. C/1999 S4 (LINEAR) observed with the JKT on 2000 July 23.9 in U. In this and all figures North is to the top and East to the left.

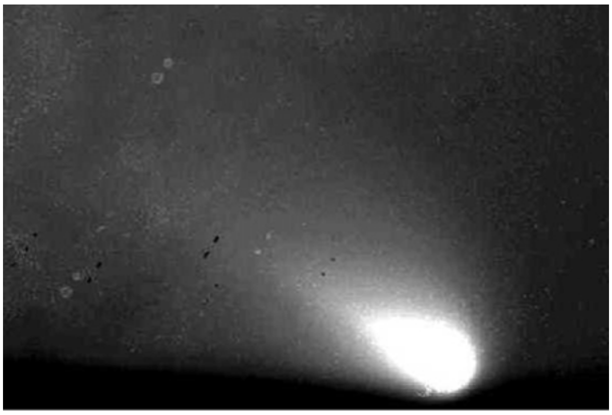

Figure 3. C/1999 S4 (LINEAR) observed with the JKT on 2000 July 24.9 in R.

Figure 4. C/1999 S4 (LINEAR) observed with the JKT on 2000 July 25.9 in R.

Figure 5. C/1999 S4 (LINEAR) observed with the JKT on 2000 July 26.9 in R.

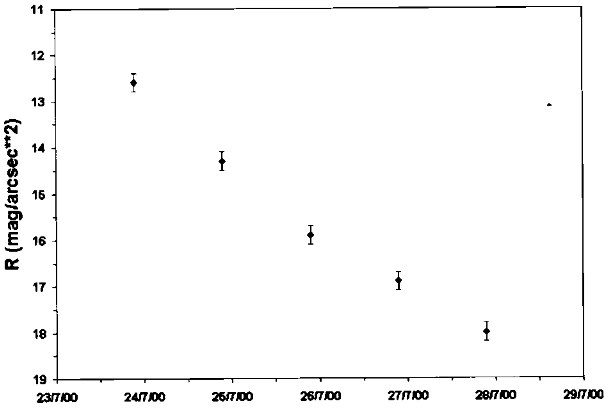

Figure 6. The variation of peak sufrace brightness of the coma of C/1999 S4 (LINEAR) during its disruption.

comet. This is measured as the average intensity of the pixels on the flat central plateau of the inner coma and converted to a surface brightness in magnitudes per square arcsecond after subtraction of the background level close to the comet. We see that the peak surface brightness of the coma dropped by more than 2 orders of magnitude in 4 days.

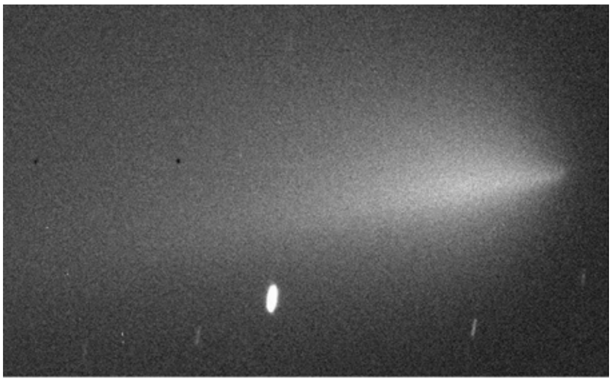

Figure 7. A deep exposure of the coma of C/1999 S4 (LINEAR) with the INT on 2000 August 01.9. No evidence of sub-nuclei is seen.

4. Sub-nuclei

The surface brightness of the expanding cloud showed a flat maximum with no evidence of sub-nuclei, in contrast to C/1993 F1 (Shoemaker–Levy). This conclusion was supported by the observations of Licandro et al. (2000) who took deep integrations in JHK with the 3.6-m Telescopio Nazionale Galileo (TNG) on 2000 July 26.9 and 27.9, which also show no evidence of sub-nuclei. A deep exposure with the INT on 2000 Aug. 1.9 (Figure 7) shows no discrete sub-nuclei down to B = 22.5, implying $H_V > 25.0$ for solar colours. The brightest sub-nuclei reported by Weaver et al. (2001) on 2000 August 5 and 6 had $H_V \approx 27$. Their rapid disappearance suggested a rapid rate of fading, although the INT, TNG and to a lesser extent JKT results suggest that even the brightest fragments were never very much brighter than when detected by the HST. $H_V \approx 27$ implies a diameter of 27-m for a rocky fragment of albedo 4%. Active, subliming fragments could be much smaller than this limit, whilst very dark fragments would be larger. The INT upper limit implies a maximum diameter of 70-m for rocky fragments of 4% albedo. Note though that the presence of a stable “lance point” structure at the head of the coma (seen most clearly in Figure 7) shows that a stable source of dust and gas emission was present at the nominal position of the comet. This led to the successful prediction (Kidger, 2000) that small sub-nuclei would be found in this position, as was later confirmed by Weaver et al. (2001).

5. The Zero Point of Expansion

Measurement of the expansion rate of the expanding cloud is difficult due to the rapid drop in surface brightness and the difficulty in measuring its centre accurately in the later JKT frames. However, combination of the JKT and INT data gives a mean expansion rate of 10.2 arcsec/day from 2000 July 26.9 to August 01.9

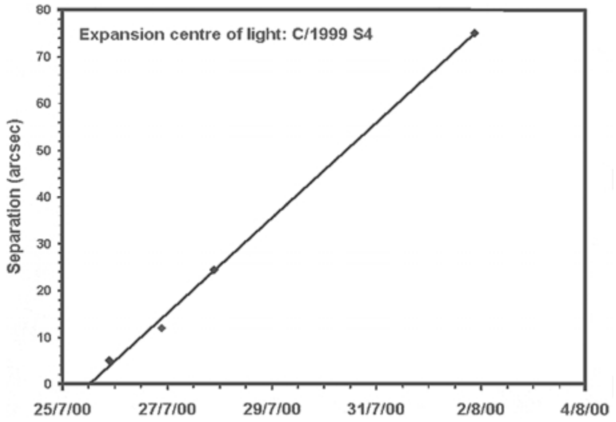

Figure 8. The rate of expansion of the peak of sufrace brightness (magnitudes per square arcsec) in R of the coma of C/1999 S4 (LINEAR) during its disruption.

(Figure 8). This leads to a nominal initiation date for the expansion of 2000 July 25.5. Assuming that the expansion is in the anti-solar direction, the deprojected expansion velocity of the centre of brightness is 77 m/s – consistent with the cloud being composed of dust.

6. Discussion

A review of cometary splittings is given by (Boehnhardt, 2002). Some comets (e.g., 51P/Harrington, 73P/Schwassmann–Wachmann 3) seem to be able to survive major and even repeated fragmentation events and may even develop into stable nearly co-orbital independent comets (e.g., 42P/Neujmin 3 and 53P/Van Biesbroeck that survive for many revolutions). Others (e.g., D/1993 F1 (Shoemaker–Levy 9)) suffer catastrophic disruption, but do not disintegrate completely, maintaining consolidated and apparently largely stable sub-nuclei. A third category (e.g., C/1996 B2 (Hyakutake)) suffered minor fragmentation(s) similar to the event observed in C/1999 S4 (LINEAR) in early July 2000, but without further disruption. These objects provide strong support for the rubble-pile model of the nucleus, which exists in three main variants that mainly differ in the strength and type of bonding forces. In contrast to the well-bound cometary nuclei that are able to survive major splittings, C/1999 S4 (LINEAR) seems to be more akin to a loosely bound dust ball and may be related to the class of comets that apparently disappear without explanation, an example of which is C/1997 N1 (Tabur), which was a 10th magnitude object that disappeared during the August 1997 Full Moon.

The properties shown by C/1999 S4 (LINEAR): depletion in low-temperature volatiles, fragmentation, very large non-gravitational forces, disintegration with minimal remnant, etc. suggest that at least at the time of its finally disintegration it was an unusually poorly consolidated object with loosely bound blocks of *relatively* small size.

Although observations up to 2000 June show that the comet was completely normal (Peschke et al., 2002), other observations demonstrate that the disruption of the nucleus was not met with the major outburst of water emission that would be expected with virgin sub-surface volatiles being released (Mäkinen et al., 2000; Farnham et al., 2001). This suggests that the mechanism for the disruption may simply have been the exhaustion of the icy "glue" that maintained the integrity of the nucleus. (Mäkinen et al., 2000) suggest that 90% of the water in the nucleus had sublimed before the terminal outburst on 2000 July 21.

Estimates of the size of the original nucleus vary widely. The very large non-gravitation terms and sudden disintegration into very small fragments suggest that the original nucleus was small. Farnham et al. (2001) suggest a lower limit of 0.44 km. A significantly larger value is given by Peschke et al. (2002), but Bockelée-Morvan et al. (2001) give a diameter from 0.2–0.6 km from outgassing and the mass budget. Fernández et al. (1999) finds a lower limit to the size of Jupiter family comets of $\sim$600-m and suggests that below this limit cometary nuclei are not stable, consistent with the fate of C/1999 S4 (LINEAR). It seems that the best estimate for the diameter of the nucleus before disintegration was in the range from 0.4–0.6 km.

A suitable model for the nucleus of C/1999 S4 (LINEAR) at the moment that it disintegrated might be the tradition Spanish Christmas sweet, the pólveron. These appear to the uninitiated to be solid, but often break apart embarrassingly into dust in one's lap when bitten. The model is especially apt for those pólverons covered with crushed almond, or seeds, that represent the rocky fragments that survived the disintegration of the nucleus.

7. Conclusions

We have discussed the disintegration of the nucleus of C/1999 S4 (LINEAR). A complete disruption of the nucleus into an expanding dust cloud was detected on 2000 July 25.9. Extrapolation of the expansion of this cloud to its origin suggests that the expansion started around 2000 July 25.5, although evidence suggests that the complete disruption of the nucleus initiated between July 18th and 22nd. The surface brightness of the expanding cloud decreased by more than a factor of 3 per day. No evidence is found, either in these observations, or in other observations taken at the same time with alternative techniques, of bright sub-nuclei that may have evolved into the mini-comets reported by Weaver et al. (2001).

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