THE DUST COMA OF COMET C/1999 S4 (LINEAR) *

RITA SCHULZ
Research and Scientific Support Department of ESA, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands

JOACHIM A. STÜWE
Leiden Observatory, P.O. Box 9513, 2300 RA Leiden, The Netherlands

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Abstract. Comet C/1999 S4 (LINEAR) showed a very special behaviour between 28 June and 1 July 2000. Optical observations of the dust coma in two distinct continuum bands revealed that it changed morphologically as well as in colour. The two-dimensional coma morphology indicates a splitting of the nucleus which probably occurred shortly before the observations of 28 June 2000. The distribution of the dust particles in sun and tail direction reflected by the slopes of the radial profiles indicate the presence of a considerable amount of disintegrating dust particles in the sunward hemisphere and an overabundance of dust, reflecting at 440 nm, within the first 18,000 km of the dust tail. The spatial profiles of the (BC–RC) colour index in sun direction are distinctly different on 28 June and 1 July, indicating the production of a large amount of particles observable in blue continuum after 28 June.

Keywords: Dust coma, split comets

1. Introduction

One of the most spectacular cometary splitting events was the complete disruption of the nucleus of comet C/1999 S4 (LINEAR), a probably dynamically new comet discovered at $r = 4.3$ AU on 27 September 1999 by the **Li**ncoln **N**ear **E**arth **A**steroid (LINEAR) programme. Evidence of the nucleus' disruption was first detected during observations between 23 and 27 July 2000 (Kidger, 2000). Optical observations of the comet's debris taken with HST and VLT on 5 and 6 August 2000 revealed that apart from the bright (dust) tail dominating its visual appearance, more than a dozen individual fragments were spread around the predicted position of the original nucleus (Weaver et al., 2001). All these fragments have faded rapidly and were no longer detected on further VLT images obtained on 9 and 14 August 2000.

From the position angle of the tail axis the time of the outburst producing the dust tail (which is commonly referred to as the time of disruption) was determined to 22.8 ± 0.2 July 2000 (Weaver et al., 2001). However, the cross correlation of two pairs of fragments detected on 5 and 6 August 2000, and subsequent estimation of their separation times indicated that these fragments separated already some time

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* Based on observations at Wendelstein Observatory.

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TABLE I

Imaging observations of C/1999 S4 (LINEAR)

Date	UT	Filter	τ_{exp} (s)	Airm.	r (AU)	Δ (AU)	Phase
28.06.2000	00:43	RC	900	2.292	0.94	1.10	59°.2
28.06.2000	01:01	RC	900	2.106	0.94	1.10	59°.2
28.06.2000	01:37	BC	1200	1.789	0.94	1.10	59°.3
28.06.2000	01:59	BC	1200	1.650	0.94	1.10	59°.3
07.01.2000	00:45	BC	1200	2.096	0.91	0.99	64°.6
07.01.2000	02:10	RC	900	1.537	0.91	0.99	64°.7

between late June and mid-July 2000 (Weaver et al., 2001). Indeed it turned out that the comet had splitting events already before its final disintegration was observed (Weaver et al., 2001). Here, we report on imaging observations of comet C/1999 S4 (LINEAR) which indicate a splitting of the nucleus on 28 June 2000.

2. Observations and Data Reduction

C/1999 S4 (LINEAR) was observed with the **Mon**ochromatic **I**mage **Ca**mera (MONICA) mounted on the 0.8-m telescope at Wendelstein Observatory, Germany, on 28 June and 1 July 2000. Images (field of view: 3′.1 × 4′.7, pixel size: 0″.5) were taken in blue continuum (BC) and red continuum (RC) with two special narrow-band filters. The band passes of these filters cover regions of the cometary spectrum known to be free of gaseous emission. A summary of the observations is given in Table I. Table II lists the basic properties of the two narrow-band filters. In addition to the cometary observations we took images of the spectrophotometric standard star BD +33 2642 in both filters at different air masses for calibrational purposes. These images showed that, although the sky appeared to be clear during the observations on 28 June, some thin cirrus must have been present. The observations of 1 July were effected by thin clouds occasionally moving into the field of view. The brightness values presented in this paper are therefore too low on the absolute scale and the apparent decrease of the comet brightness between 28 June and 1 July may be due to clouds. However, all relative values, such as profile shapes and spatial colour variations are not affected by weather conditions. The tracking errors of the telescope, assessed from the length and shape of the star trails, was determined to be below 1″ for the longest exposure time, i.e., 1200 s.

All images were bias subtracted and flat-fielded. The air-mass coefficient, k_λ, of the filters (Table II) can be determined from the images of the spectrophotometric standard star, as the slope of a [log(ADU/s) vs. Air mass] plot. The absolute values for the flux of BD +33 2642 as a function of wavelength were taken from Oke (1990). By relating these flux values convolved with the appropriate filter curve to the count rates in the corresponding images of the standard star, we were able to determine a count rate to flux conversion factor for each filter (Table II). These were then used for a flux calibration of the comet images. The flux tables for the Sun (Colina et al., 1996) and for Vega (Hayes, 1985) can further be used to establish the zero-point fluxes for a conversion of fluxes to magnitudes, since for Vega all colour indices should be zero *per def.*, which then enable the computation of the (BC–RC) colour indices. The C.I. of the sun was then computed to: $(BC–RC)_{\odot} = 1.13 \pm 0.01$.

Since the comet did not cover the entire CCD, the amount of night sky flux could be determined from the images directly by computing the average over the whole frame excluding objects. This procedure neglects possible variations of the sky over the frames, but since the sky in the frames was uniform within a margin of a few percent, this appears to be a justifiable approach.

TABLE II

Properties of narrow-band filters

Filter	λ_{eff} (nm)	W_{λ} (nm)	k_{λ} (mag/Airm.)	Flux/cps. 10^{-16} $\frac{\mathrm{erg/(cm^2\ s)}}{\mathrm{ADU/s}}$
BC	444.0	2.6	1.62 ± 0.41	22.6 ± 10.0
RC	685.6	7.2	0.18 ± 0.03	51.5 ± 18.0

3. Analysis and Results

3.1. TWO-DIMENSIONAL ANALYSIS

Figure 1 shows the dust coma of Comet C/1999 S4 (LINEAR) as it appeared in the blue and red continuum on 28 June and 1 July 2000. It is obvious that the coma morphology has changed significantly within the three days between both observing runs. On 1 July 2000 the dust coma is so strongly elongated already in the inner part that it is very difficult to determine an optocenter in these images. (The optocenter is defined as the brightest spot in the coma.) On 28 June 2000 the images appear to be rather “ordinary”, on the first view, showing an elliptical coma and the dust tail. However, the immediate vicinity of the brightest pixel is already somewhat displaced towards the south east with respect to the extended rest of the coma. The optocenter is at very different positions on both observing dates. Altogether, this might suggest that shortly before the observations of 28

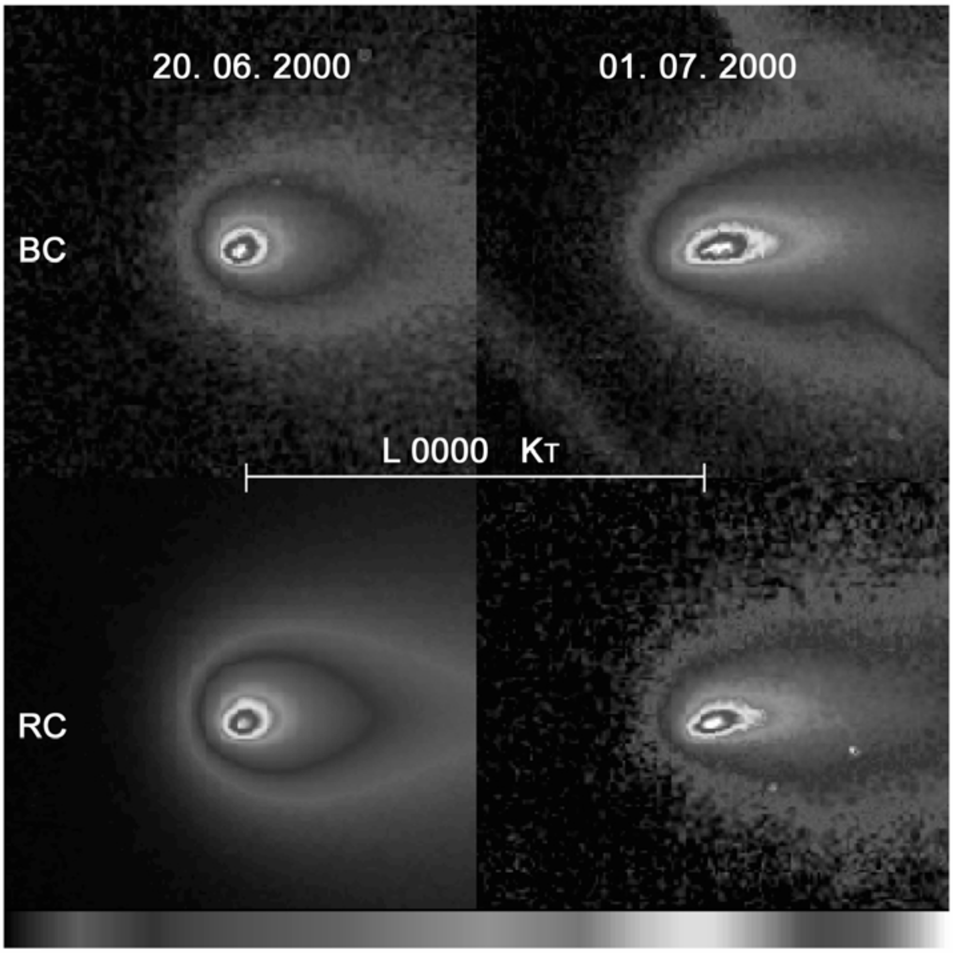

Figure 1. Comet C/1999 S4 (LINEAR) imaged in blue continuum (BC) and red continuum (RC). On 1 July 2000, the coma is much more elongated than on 28 June 2000. The Sun is to the left in all images.

June were obtained, the nucleus or a highly active fragment started to drift with respect to the rest of the coma that still moves undisturbed along the original orbital path of C/1999 S4 (LINEAR). As the undisturbed coma was released prior to the disruptive event it represents older material. The more recently released dust forms a new tail arranged along the path of the active fragment, which is different from the original orbital path of C/1999 S4 (LINEAR). Consequently, the displacement is more pronounced in the images of 1 July 2000.

3.2. COMA PROFILES

Spatial coma profiles were obtained from the images of 28 June and 1 July 2000. The profiles shown in Figure 2 represent the radial distribution of the dust as seen in blue and red continuum in the sunward hemisphere and in tail direction. (The five innermost points of the profiles, $\approx 2\overset{\prime\prime}{.}5$, reflecting the seeing and uncertainties owing to tracking errors, are not plotted.) The sunward profiles were obtained by azimuthal averaging over the sunward hemisphere (whereby the brightest pixel of each image was assumed to contain the nucleus). The profiles in tail direction were averaged over ± 2 CCD rows, centered along the symmetry axis of the coma, which was determined as follows. First, all images were oriented along the direction of the projected extended radius vector of the comet, with the tail pointing along the (positive) x-axis. Then a first estimate of the "center" row (in other words, symmetry axis) of the coma by eye was assumed and the image was mirrored along this row, i.e., the y-axis was "flipped" upside down. A "reference" image was computed by taking the minimum of the original and flipped images for each pixel position (x, y) and this reference was subtracted from the original. The resulting residual images show quite distinct artefacts, which enable a new estimate of the symmetry axis and the whole procedure was repeated until the undisturbed coma vanished completely from the residual images leaving only the "displaced" material.

From Figure 2 it is evident that the profiles in tail direction are much flatter on 1 July than on 28 June, whereas the sunward profiles only slightly differ on both dates. To quantify the shapes of the profiles we have fitted them by a ρ^{-m} law, which results in straight lines with certain slopes, m, in the double logarithmic representation chosen for Figure 2. The slopes and minimum distances to which a good fit could be obtained are given in Table III. It turned out that almost all profiles were well fitted by this law down to projected nucleus distances between 3,700 km and 6,000 km. The tailward profile of 1 July in blue continuum could, however, be fitted by a ρ^{-m} law only at distances greater than 18,000 km. Inside this distance the BC brightness profile is very flat indicating that the number density of the dust particles represented by this colour are not diluting with r^{-2}. This can only be the case if they are continuously replenished.

Another peculiarity is that the slopes resulting for the sunward profiles are all much higher than expected. In a steady-state coma the decrease of brightness should follow a ρ^{-m} law with $1 \leq m \leq 1.5$ (Jewitt and Meech, 1987), which is indeed the case for the outer parts of the tailward profiles. In the sunward hemisphere, however, the brightness decreases at a much higher rate. The determined slopes are of order of 2.3 on 28 June and 2.7 on 1 July. Such high slopes are unexplainable at steady-state conditions indicating that the dust grains seen in the sunward hemisphere are further disintegrating while moving away from the nucleus. The sunward profiles in Figure 2 extend to a nucleus distance of about 20,000 km. Thus, most of the dust in these profiles has been ejected from the nucleus within less than 1 day, if a dust velocity of about 0.5 km/s is assumed.

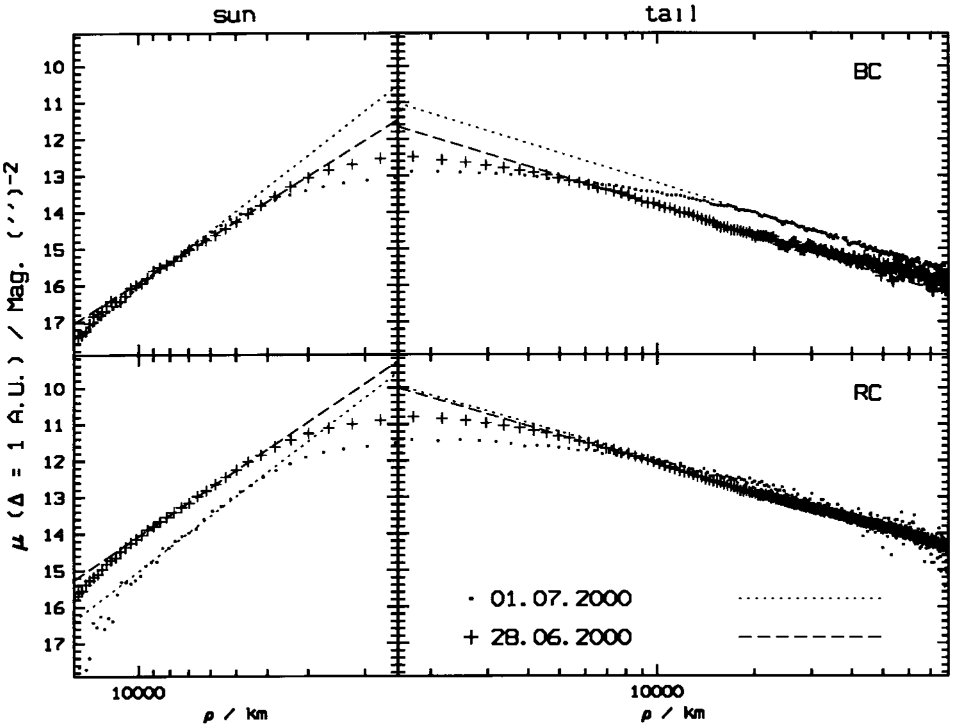

Figure 2. Spatial profiles in sun and tail direction with straight lines fitted to them. The surface brightness, μ is plotted as a function of the projected distance to the nucleus. The sunward profiles were azimuthally averaged over the sunward hemisphere. The profiles in tail direction were centered along the symmetry axis of the coma (see text for details).

TABLE III

Slopes of straight line-fits to profiles in Figure 2

Date	Filter	m_{Tail}	ρ_{min}	m_{Sun}	ρ_{min}
28.06.2000	BC	1.08 ± 0.02	5500	2.22 ± 0.03	4000
	RC	1.05 ± 0.01	4000	2.40 ± 0.02	4000
01.07.2000	BC	1.09 ± 0.01	18000	2.75 ± 0.04	5500
	RC	1.02 ± 0.02	6000	2.72 ± 0.06	3700

This indicates that the amount of *unstable* dust increased between 28 June and 1 July. A detailed modelling of the dust distribution is required to quantify this effect and further investigations are planned for the future.

3.3. DUST COLOUR

Figure 3 shows the (BC–RC) colour index profiles in sun and tail direction determined directly from the profiles of Figure 2. In tail direction the dust colour is as expected, redder than the Sun and constant along the profiles. In sun direction the dust colour profiles have very different shapes. On 28 June the (BC–RC) colour index increases with distance from the nucleus peaking at 4,000–5,000 km. On 1 July it shows the opposite behaviour, decreasing with distance to the nucleus reaching its minimum at 6,000–7,000 km. In both cases the distance of the maximum/minimum of the curve coincides with the distance from which on straight lines could well be fitted to the brightness profiles of Figure 2. Further in, the coma is obviously dominated by non-steady-state conditions. We therefore refrain from speculating about the particle and colour distribution inside these boundaries. Although the error of the colour index is rather large (see error bar depicted in Figure 3) the difference in the dust colour between 28 June and 1 July is still pronounced if the worst case error is assumed. For 28 June there is a rather straightforward explanation for the colour index profile. If dust particles continue to disintegrate while moving away from the nucleus, larger (redder) particles should predominantly be present at closer distances while the region further away from the nucleus should exhibit more smaller (blue) particles. In this scenario the vertex of the curve (reddest value) indicates the border between the regions more dominated by the red or blue particles. Note, that the value of the (BC–RC) colour index is generally higher than in tail direction ($\sim$0.3 at the peak position) indicating that there are more red particles in sun than in tail direction on this date.

The shape of the colour profile on 1 July indicates that more small (blue) than large (red) particles must be present in the sun than in the tail direction. The decrease of the (BC–RC) colour index towards “bluer” values could, in principle, be produced by gas emission bands. However, since we used narrow-band continuum filters of which the gas contamination is minimal, only a huge outburst of gas with emission bands in the BC filter could have caused such a pronounced effect. We therefore argue that the decrease of the (BC–RC) colour index towards “bluer” values reflects the production of additional particles that reflect light in this wavelength range. The position of the minimum would thus represent the peak of “blue” particle production, hence define the lifetime of the respective disintegrating grains. The latter need not necessarily be visible in the optical, but could be very large particles that might be observable at IR wavelength.

3.4. DISCUSSION AND CONCLUSIONS

The analysis of the imaging observations of Comet C/1999 S4 (LINEAR) from 28 June and 1 July 2000 resulted in clear evidence for a distinct difference between the dust coma morphology on both dates. The change observed in the two-dimensional coma morphology (Figure 1) suggests that a disruptive event took place shortly before the observations of 28 June 2000. This presumption is further supported

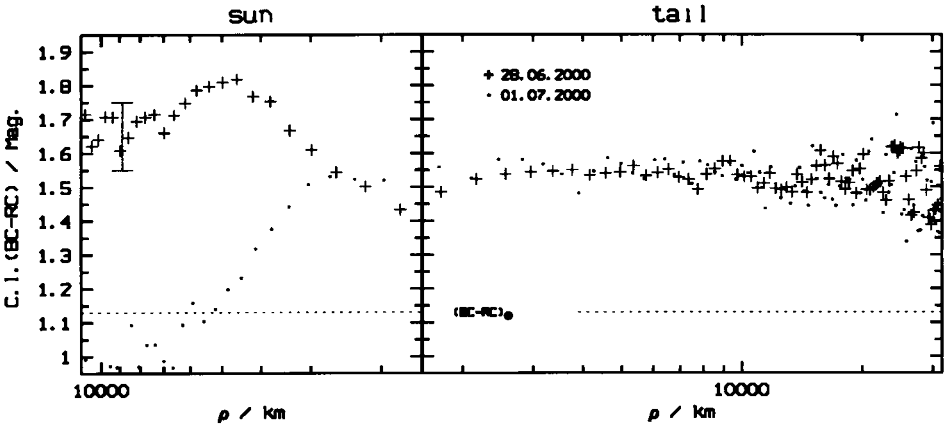

Figure 3. Spatial colour index profiles in sun and tail direction. The BC–RC colour index is plotted as a function of the projected distance to the nucleus. The profiles were constructed from the brightness profiles shown in Figure 2.

by the radial distribution of dust particles in sun and tail direction and by the different variations of the spatial colour distribution within the coma. The fact that the tailward profile obtained in the blue continuum is very flat out to a distance of about 18,000 km indicates the presence of an additional source of dust which may be one or more small fragments. The low resolution of the images does, unfortunately, not allow the detection of such fragments in our observations. However, HST observations reveal that fragmentation of the nucleus was already on-going well before the complete disintegration of the comet at around 23 July 2000. At least one fragment at ~460 km projected distance tailward from the nucleus was detected on 7 July 2000 by HST (Weaver et al., 2001). With a typical separation velocity of 0.5–1 m/s (cf. Sekanina, 1982) this fragment would have been close to the nucleus at the time our observations took place.

The brightness profiles reflecting the distribution of dust as a function of distance to the nucleus are very different in sun and in tail direction and also vary significantly between both dates of observation. The slopes of the sunward profiles indicate the presence of a considerable amount of disintegrating dust particles on both dates, which is, however, increasing between 28 June and 1 July. The existence of such particles is also confirmed by the difference between the radial distribution of the (BC–RC) colour in sun and in tail direction and the distinctly different shape of the sunward colour profiles on 28 June and 1 July.

All these results are consistent with the assumption that a splitting of the nucleus occurred a short time before the observation of 28 June 2000, which produced at least one major fragment and probably a number of small fragments drifting in the approximate tail direction. The fragments remained active at least until 1 July 2000 producing further disintegrating dust particles. A splitting of the nucleus around this time would also be consistent with the finding that two pairs of fragments detected on 5 and 6 August 2000 separated already sometime between late June and mid-July 2000 (Weaver et al., 2001).

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