NUCLEUS AND TAIL STUDIES OF COMET P/SWIFT-TUTTLE

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(Received 14 August 1995)

Abstract. CCD images of comet P/Swift-Tuttle, obtained in April 1994 with the 2.2m telescope at ESO La Silla/Chile, showed a comaless stellar nucleus. From absolute photometry we estimated the equivalent radius of the cometary nucleus to be about 11 km (assuming an albedo of 0.04 as for P/Halley) for two rotation phase angles which differ by about 75 deg. From that we conclude that the nucleus is either of rather spherical shape or that the viewing geometry was almost pole-on during our observations.

An analysis of the plasma tail and inner coma of the comet by means of photographic plates and CCD images through IHW and BVR filters, obtained with the 80cm Schmidt camera and the 1.2m telescope at Calar Alto/Spain in November 1992, revealed several tail rays, head streamers and substructures in brightness excess areas in the coma. While some of the tail rays extended to several million km nuclear distance, most of them can be traced to starting points which lie in a region just 20000-35000 km projected distance tailward from the nucleus.

Key words: Comet P/Swift-Tuttle, nucleus, plasma tail

1. Introduction

About 130 years after its last apparition in 1862 comet P/Swift-Tuttle passed perihelion again on 12 December 1992. This 1992 perihelion passage was well observed by many professional and amateur observers who collected scientific data with different observing techniques.

In the meantime several authors presented papers on P/Swift-Tuttle observations obtained in late 1992 and early 1993 around perihelion and when the comet was outside the water sublimation limit in 1994. The results published so far refer to the light curve of the comet from amateur brightness estimations (Kammerer and Möller, 1994), to the nucleus size (O Ceallaigh *et al.*, 1995), the rotation and active sources of the nucleus (Boehnhardt and Birkle, 1994; Jorda *et al.*, 1994; Yoshida *et al.*, 1993) from CCD imaging, to the production rates and expansion velocity of the coma gas from spectroscopy (Schulz *et al.*, 1994), and, also from spectroscopy, to the kinematics of the ion tail (Spinrad *et al.*, 1994). Bockelee *et al.* (1994) published OH production rates derived from radio observations of the comet. As an important outcome of the 1862 observations Sekanina (1981) published the first nucleus rotation and activity source model for this comet which is compared with the 1992 observations of the comet by Boehnhardt and Birkle (1994).

The observations described in this paper aimed at the assessment of the cometary activity far from the sun (outside 5 AU), of its nucleus size and of tail structures

Earth, Moon and Planets **73:** 51–70, 1996.

in the comet shortly before perihelion passage. Although collected as a kind of serendipituous activity in the course of other observing programmes, the data may add further mosaic stones to the picture of P/Swift-Tuttle, which is frequently called "the second Halley".

2. Nucleus Studies

The detection of the bare nucleus of a comet requires either a dedicated space mission for a fly-by or rendezvous or a large telescope pointing to such a small object when it is far from the Sun (typically beyond 5 AU) and, therefore, very faint (usually fainter than 20 mag). An important issue for the detection of the nucleus signal is the non-existence of a cometary coma around it. Even a weak coma can severely degrade the chance of nucleus detection and it definitely reduces the accuracy of the measurements of the nucleus brightness.

The following analysis is based upon CCD images of comet P/Swift-Tuttle at about 5.8 AU solar distance. Figure 1 shows the comet in a section of four co-added R filter frames of 14 April 1994 after alignment of the cometary images to the same pixel coordinates.

2.1. OBSERVATIONS AND DATA REDUCTION

The observations of the comet were performed in April 1994 under photometric conditions at the 2.2 m telescope in ESO La Silla, Chile, through a Bessel R filter.

Table I provides an overview of the dates, of the viewing geometry of the comet and of the telescope equipment. As the comet was at low galactic latitude (b $\simeq$ -10 deg), short exposure times (typically 240s) were chosen in order to avoid blends with background stars for accurate photometric measurements and to allow for accurate astrometry of the comet.

The data reduction comprised bias level subtraction and flatfield division. Extinction correction and absolute brightness calibration were achieved using the standard star PG1323.

2.2. COMA SEARCH

While the coma development of comet P/Swift-Tuttle was very strong around perihelion in 1992 (see Boehnhardt and Birkle, 1994; Yoshida *et al.*, 1993; Schulz *et al.*, 1994), coma activity is not evident in our April 1994 images when the comet was at about 5.8 AU solar distance outbound (Figure 1). Nevertheless, a careful search for a faint coma around the comet was undertaken with our images of P/Swift-Tuttle. This coma search involved different steps: (a) visual inspection of the images, (b) comparison of the relative flux in the potential coma region close to comet with general sky background in the images, (c) comparison of the wings in

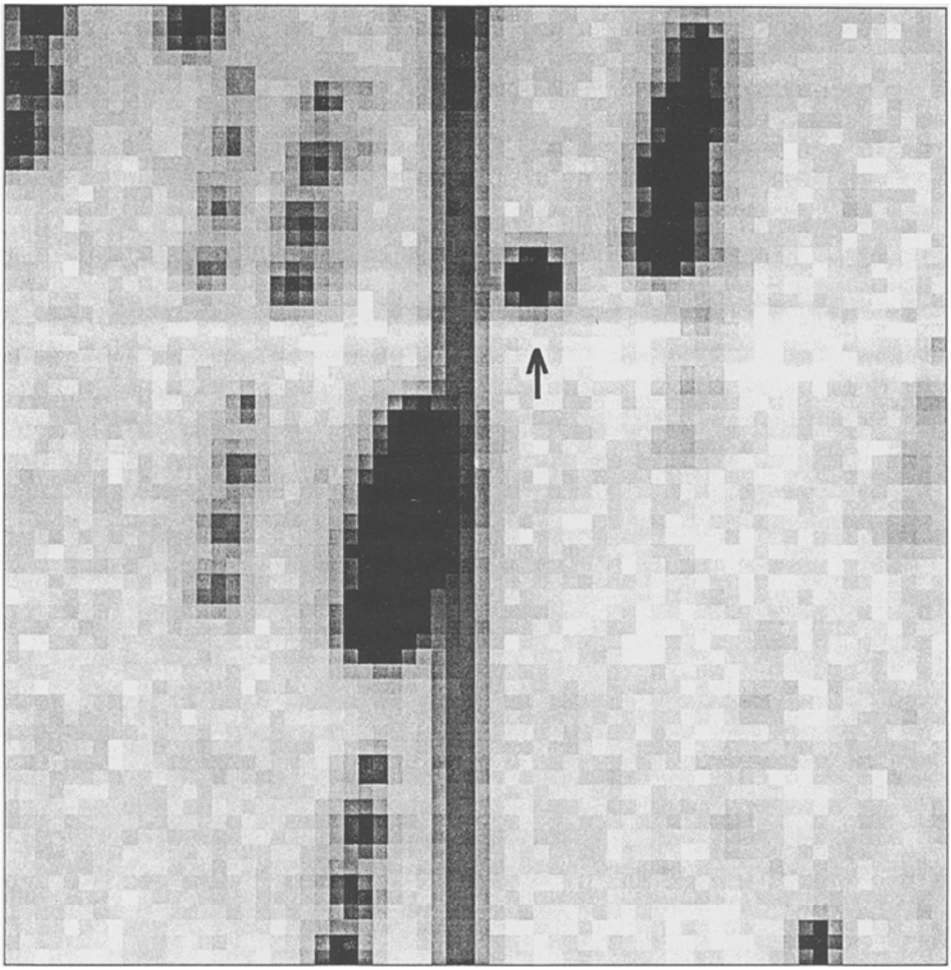

Fig. 1. Comet P/Swift-Tuttle on 14 April 1994: four R filter exposures were aligned to have the comet at the same pixel coordinates and were then co-added. The comet appears as stellar source (marked by an arrow) while the stars show up as "strings of pearls". The total exposure time was 840 s. CCD binning was 2 × 2 pixels. North is up, east to the left. Field size is 42 × 42 arcsec. The vertical streak close to the comet is caused by CCD blooming due to a nearby bright star.

the intensity profiles of the cometary images with the point spread function (PSF) of stellar images.

(a) Inspection of the immediate surrounding of the comet image with very narrow cut levels close to the background revealed no indication for a coma.

(b) Statistical analysis of the regions where a faint coma should appear showed that the relative brightness in a 10 × 10 pixels wide box close to the comet is within the level range of the typical sky background further away from the comet. With the same box size the signal of the comet lies at least 4 mag above background level. From that one can estimate the detection limit for a possible coma to be

TABLE I

Viewing geometry and telescope equipment for the observations of comet P/Swift-Tuttle

Date (UT)	26.77/11/1992	9.16/4/1994	14.18/4/1994
Sun Distance (AU)	0.995	5.771	5.814
Earth Distance (AU)	1.306	5.365	5.414
Elongation (deg)	49	109	109
Phase (deg)	48	9	9
PA[a] of Sun (deg)	231	249	255
Observatory	Calar Alto	La Silla	La Silla
Telescopes	80cm Schmidt; 1.2m	2.2m	2.2m
Instruments	imaging; CCD camera	EFOSC2	EFOSC2
Detector (plate, CCD)	IIIaJ; Tektronix 27 μm	Thomson 19 μm	Thomson 19 μm
Scale	86 ("/mm); 0.56 ("/pix)	0.34 ("/pix)	0.34 ("/pix)
Filters	none; IHW, BVR	R	R

[a] PA = position angle measured north over east.

below 5 percent of the comet brightness. Assuming the semi-empirical law for the flux F(ρ) of dust reflected coma light through a circular aperture of radius ρ

$$F(\rho) \sim \rho^c \tag{1}$$

with c = constant close to unity (c would be exactly 1 for a homogeneous coma which expands isotropically with constant velocity), one would expect to detect a faint coma signal above background to about 10 pixels nuclear distance in our images. Despite all uncertainties about the validity of Equation (1), the non-detection of a faint but measurable coma within 10 pixels around the nucleus of P/Swift-Tuttle may be considered as a hint that the coma, if present at all, was far below detection limit or was confined inside the seeing disk of the comet.

(c) For the comparison of the intensity profile of the comet with those of stars we increased the signal-to-noise ratio of the objects. This was achieved by co-addition of all available P/Swift-Tuttle frames from the two nights in April 1994 (in total 1740 s exposure time) after careful alignment of the center of the cometary seeing disks. The resulting flux was normalized by subtracting the respective background level and scaling the maximum in the cometary image to unity. In order to get suitable PSFs of stars for the comparison we added up four short exposed images of 14 April 1994 (840 s total exposure time) now with the stars aligned to each other. After normalization as for the comet, stellar intensity profiles were extracted by cuts through four star images in the neighbourhood of the comet. Furthermore, we extracted normalized profiles of two stars from a 600 sec exposure of 9 April 1994. The cuts through the stellar images were made perpendicular to the star trails caused by the telescope tracking on the comet, thus avoiding elongation

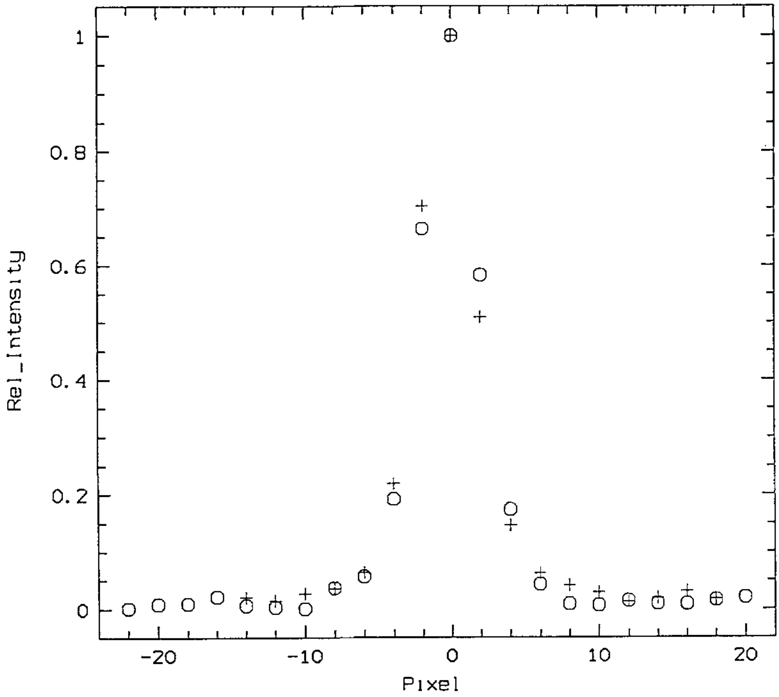

Fig. 2. Comparison of the intensity profiles of comet and star images: the profiles were obtained from co-added frames of two observing nights as described in Chapter 2 (see coma search method c). No difference – even in the wings – is found between comet (circle) and star (symbol +) profiles. One pixel is 0.34 arcsec on the sky.

effects and conserving the information necessary for the PSF comparison. The six stellar profiles (in total 1440 s exposure time) were finally averaged – weighted by their respective integration times – to a mean stellar profile. Figure 2 shows the normalized intensity profiles of the comet and the "mean star".

The cores of the intensity profiles are identical for the cometary and stellar images (with FWHM = 1.65 arcsec for the "mean star" and FWHM = 1.71 arcsec for the comet, which is consistent with a seeing of about 1.5 arcsec for 2 × 2 pixels CCD binning). But also the wings of the profile of the comet, which should be most sensitive to weak contributions from a faint coma, do not differ from the stellar ones.

From the results of methods (a)–(c) we therefore conclude that during our observing period in April 1994, no significant coma activity was present around the nucleus of P/Swift-Tuttle. If any, it either must have been concentrated inside the seeing disk of the comet of about 5 pixels diameter (almost 6600 km at the comet). Or the coma was fainter than 5 percent of the nucleus signal and cannot be separated from the general sky background. The former case is rather unlikely since it would require a very condensed coma which is in contradiction to dust coma modelling for P/Swift-Tuttle. According to Finson-Probstein calculations (for the model description see Beißer, 1990) the visible dust around P/Swift-Tuttle at 5.8 AU outbound from the Sun should be confined in an almost circular coma of some 300000 km diameter at 3 percent peak brightness level.

Compared to P/Halley at 5 AU (own observations, unpublished) comet P/Swift-Tuttle appeared widely inactive at about the same solar distance post-perihelion. However, around perihelion the activity level of P/Swift-Tuttle was quite as high as that of P/Halley. At that time, at least three distinct and strong gas and dust jets plus one fan were identified in the coma of P/Swift-Tuttle (Boehnhardt and Birkle, 1994). This activity must have ceased at the time of our April 1994 observations. The low or zero emission level of the comet can be due to low illumination levels of the potential material emission sources on the nucleus which might have been insufficient to initiate gas sublimation on the surface of the nucleus. This implies that the nucleus surface of P/Swift-Tuttle was also inactive away from the dominant emission regions as it was the case for P/Halley (Keller, 1990). Taking into account the large difference in true anomaly between the November 1992 and April 1994 orbit position of P/Swift-Tuttle (about 158 deg), it seems possible that the active regions seen in November 1992 were permanently on the night side of the nucleus and thus not exposed to sunlight during the April 1994 observations (this is easily possible for a rotation axis orientated close to Earth direction in November 1992 as suspected by Jorda *et al.*, 1994).

2.3. NUCLEUS SIZE

Based upon the non-detection of a clear coma signal around P/Swift-Tuttle in April 1994 (see Chapter 2.2), we interpret the observed cometary brightness as due to reflected sunlight from the bare nucleus. The equivalent radius R of the nucleus can then be calculated from Equation (2)

$$R = \frac{r}{\sqrt{A}} 10^{(0.2(M_o - m_{com} + \lambda\varphi + 5\lg\Delta))} \tag{2}$$

In Equation (2), the following abbreviations are used: r is the comet distance from the Sun (in km), Δ is the comet distance from Earth (in AU), A is the albedo of the nucleus, M_o is the filter brightness of the Sun (in mag), m_{com} is the filter brightness of the comet (in mag), φ is the phase angle of the comet (in deg) and λ is the phase darkening coefficient for the cometary nucleus (in mag/deg).

The equivalent radius R of the nucleus of P/Swift-Tuttle for the April 1994 observations is calculated using Halley's albedo of 0.04 (Keller, 1990) and the empirical phase darkening coefficient of 0.03 mag/deg (Spinrad *et al.*, 1979). The results are given in Table II. With more than 11 km radius P/Swift-Tuttle is considerably larger than P/Halley – by a factor of about 1.5 (Keller, 1990) – and than P/Tempel 2 – by a factor of about 2 (A'Hearn *et al.*, 1989). Using the rotation period of 2.795 days determined by Boehnhardt and Birkle (1994) the difference in the rotation phase of the nucleus is 1.8 (or about 73 deg) for the two observing

TABLE II

Photometry and size of comet P/Swift-Tuttle

Date (UT)	9.16/4/1994	14.18/4/1994
Nucl. Brightness (mag)	19.57±0.04	19.55±0.05
Radius (km)	11.2±0.3	11.5±0.3

nights. Since the cometary brightness was essentially identical in both nights, we conclude that (neglecting albedo effects) the optical cross section of the nucleus did not significantly change due to the rather different rotation phase. This can either be explained by a rather spherical shape of the nucleus or by an almost pole-on viewing geometry of P/Swift-Tuttle during our observations. The latter interpretation would imply that – assuming a non-precessing rotation axis – the nucleus of the comet was also seen almost pole-on in October and November 1992, which is at least qualitatively in good agreement with the studies of the coma jets performed by Boehnhardt and Birkle (1994).

2.4. DISCUSSION OF THE RESULTS

With 11 km equivalent radius comet P/Swift-Tuttle belongs to the larger cometary objects found in our solar system (O Ceallaigh *et al.*, 1995). Our result for the radius confirms the value of 11.8 km determined by O Ceallaigh *et al.* (1995) from CCD photometry of the comet in February 1994. Accidently, almost exactly 21 rotation cycles of the nucleus are inbetween the two nucleus observations (14.6 February 1994 for O Ceallaigh *et al.* and 14.2 April 1994 for ours; rotation period = 2.795 days). Hence both observations viewed the same rotation phase of the nucleus which may explain the good agreement of the determined nucleus radii. Yet no conclusive information of the body axes ratio of P/Swift-Tuttle can be derived from the two data sets.

Minor coma activity was detected in February 1994 (O Ceallaigh *et al.*, 1995). Our own observations two months later did not reveal any coma around the nucleus, although being more sensitive by an overall factor of about 1.7 than those of O Ceallaigh *et al.* (1995). One may therefore assume a decreasing or even ceasing coma activity of the comet for early 1994, when P/Swift-Tuttle was beyond 5 AU from the Sun. Since at this distance dust grains remain close to the nucleus for quite a long time interval, a remnant coma can be seen around the nucleus, even if the nucleus is already inactive. This makes it difficult to assess from the two available data sets the exact date for the end of dust and gas emission. The total integration time on the comet during our observing run was not long enough to definitely exclude the presence of a very dim coma (order of a few percent) around P/Swift-Tuttle.

As pointed out in Chapter 2.2, the nuclear surface areas which were very active in 1992 may have been permanently dormant on the nightside of the nucleus in early 1994 (this, of course, assumes an almost constant direction of the nucleus rotation axis). It is therefore rather unlikely that they have produced the weak coma seen by O Ceallaigh *et al.*. Their speculation that the remnant coma in February 1994 was due to active source A in Sekanin's model of the nucleus derived from 1862 observations (Sekanina, 1981), requires careful coma modelling (using the 1862 and 1992 data sets) for verification.

3. Tail Studies

In the following we describe phenomena in comet P/Swift-Tuttle which can be related to its tail activity. The image material used was collected in November 1992, i.e. with the comet close to maximum activity about 2 weeks before perihelion passage. The combination of small-scale CCD and large-scale Schmidt plate imaging allows to trace structures in the distant tail (typically several 100000 to more than 5000000 km away from the nucleus) back to the near-nucleus region (some 20000 to 40000 km projected nuclear distance) of the comet.

3.1. OBSERVATIONS AND DATA REDUCTION

The pre-perihelion tail activity was monitored by narrow-field CCD imaging in October and November 1992 with the 1.2m telescope at Calar Alto Observatory, Spain (see Table I). Details of the observations and basic data reduction are described in Boehnhardt and Birkle (1994). The relatively calibrated images were further processed by adaptive Laplace filtering (see Boehnhardt and Birkle, 1994, and references therein) in order to enhance faint coma and tail structures (Figure 3).

A wide-field IIIaJ plate of the comet including its long ion tail was taken with the 0.8m Schmidt Telescope at Calar Alto Observatory, Spain, on 26 November 1992 almost simultaneously to the CCD observations (see Table I). Schmidt exposures of the comet on Kodak Technical Pan plate and film are also available for 24 and 25 November 1992.

Figure 4 shows a hardcopy from the Schmidt plate of 26 November 1992. A part of this plate including the coma and more than 1 deg of the tail was digitized by means of a PDS machine. As for the CCD images of the coma, adaptive Laplace filtering was used to enhance inherent tail structures. However, because of the star-rich background this method was found to be inadequate for our analysis (although tail rays close to the head of the comet can be identified in the processed images). We therefore applied an unsharp-masking technique to the scanned image, i.e.

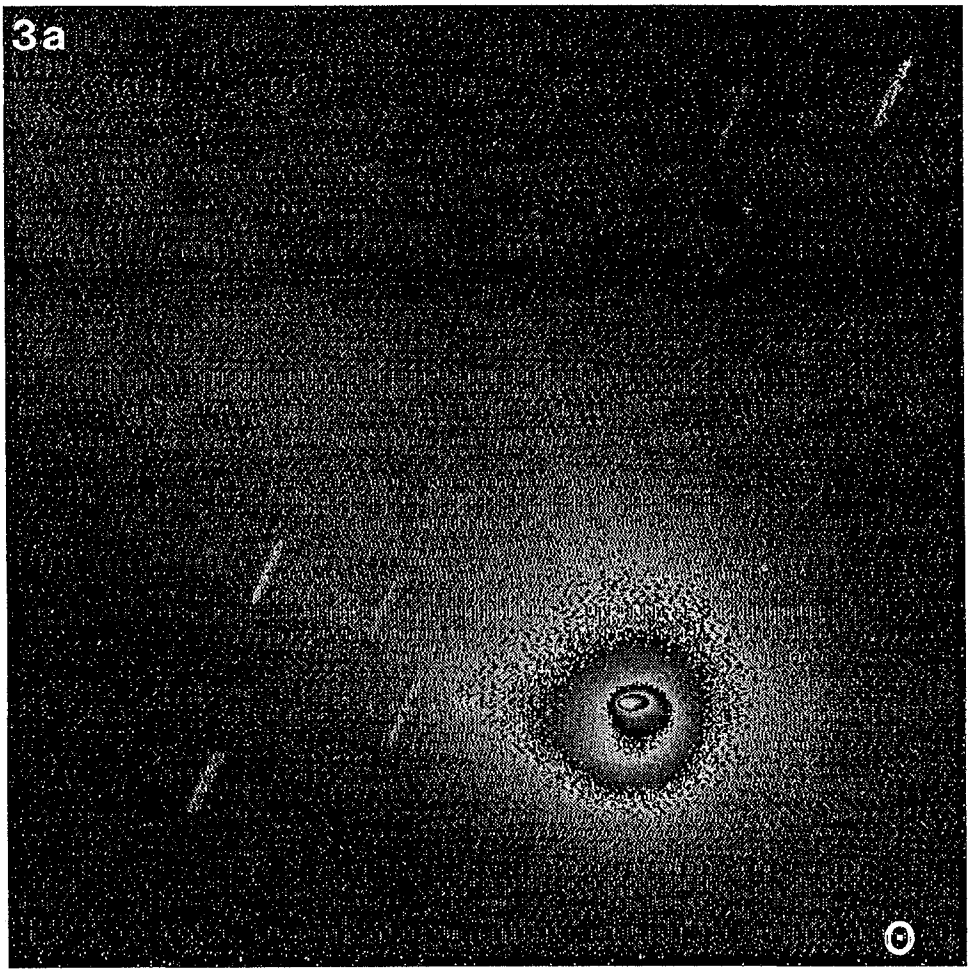

Fig. 3. CO^+ filter CCD image of comet P/Swift-Tuttle on 26 November 1992: north is up and east to the left. The Sun direction is labeled by the symbol **o**. The field of view is 4.8 × 4.8 arcmin. The original (a; this page) and the Laplace filtered (b; next page) images are presented for comparison. Tail rays are indicated by **R1-R8**, brightness excess areas by **B1-B4**. The horizontal streaks seen in the upper and lower part of the Laplace-filtered image (b) are due to unexpected CCD read-out noise encountered during the observations. Exposure time: 19.00.52-19.06.42 UT

division of the logarithmized original image by a smoothed version of it. The best results were achieved by using 10 to 20 pixel wide filters for the smoothing of the digitized image (see Figures 6).

3.2. GENERAL DESCRIPTION OF THE TAIL

In the following we describe the phenomena of – in most cases – ionic origin in the coma and tail region of the comet. The combination of small-scale CCD and

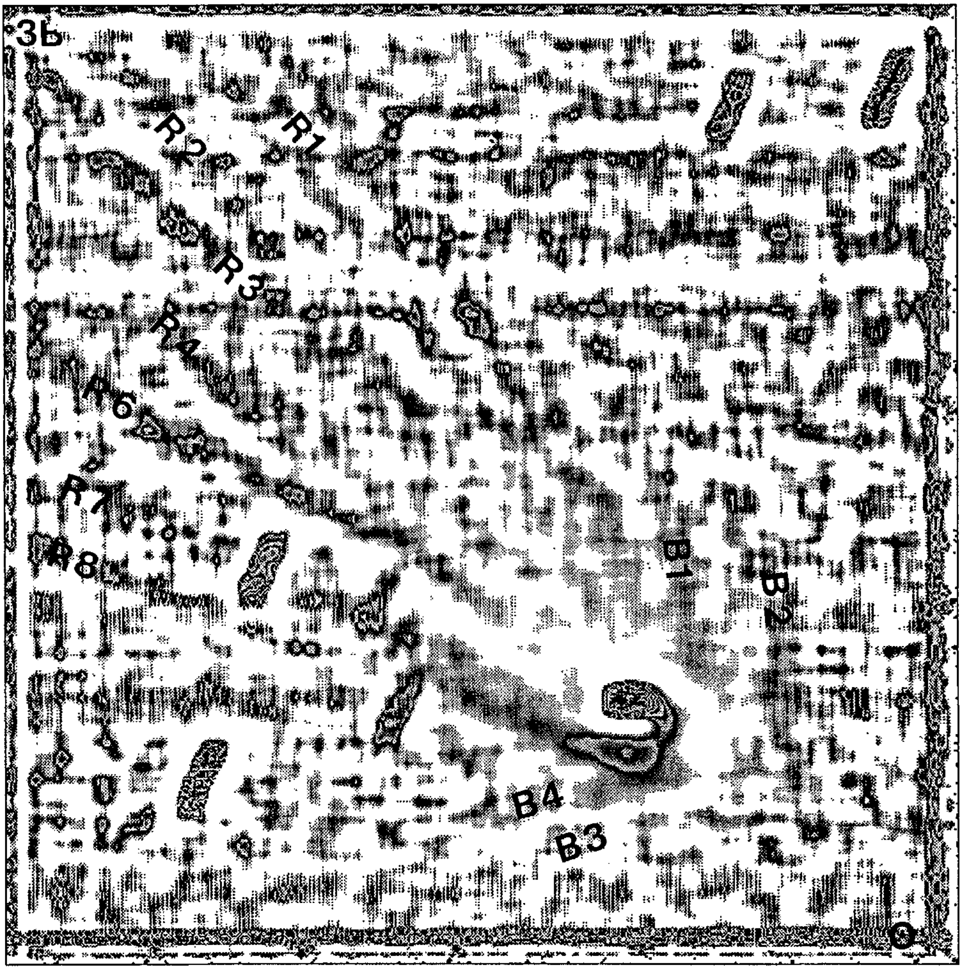

Fig. 3b.

large-scale Schmidt plate imaging allows to trace distant tail structures back to the near-nucleus region of P/Swift-Tuttle.

In Figure 4 the overall appearance of comet P/Swift-Tuttle on 26 November 1992 is presented as seen with the Calar Alto Schmidt camera. As the spectral sensitivity of the IIIaJ emulsion used is limited to wavelengths shorter than 540 nm, the coma image may essentially be an overlap of gas emission (mainly C_2, C_3 and CN), some dust reflected sunlight and minor ion emissions, while the plasma tail phenomena discussed below may best represent the distribution of CO^+ ions.

In the PDS scan of the plate the coma extended over at least $1.8 * 10^6$ km diameter as measured perpendicular to the Sun direction through the central brightness region (see Figure 5). A more than $17 * 10^6$ km long ion tail (i.e. at least 5 deg on the

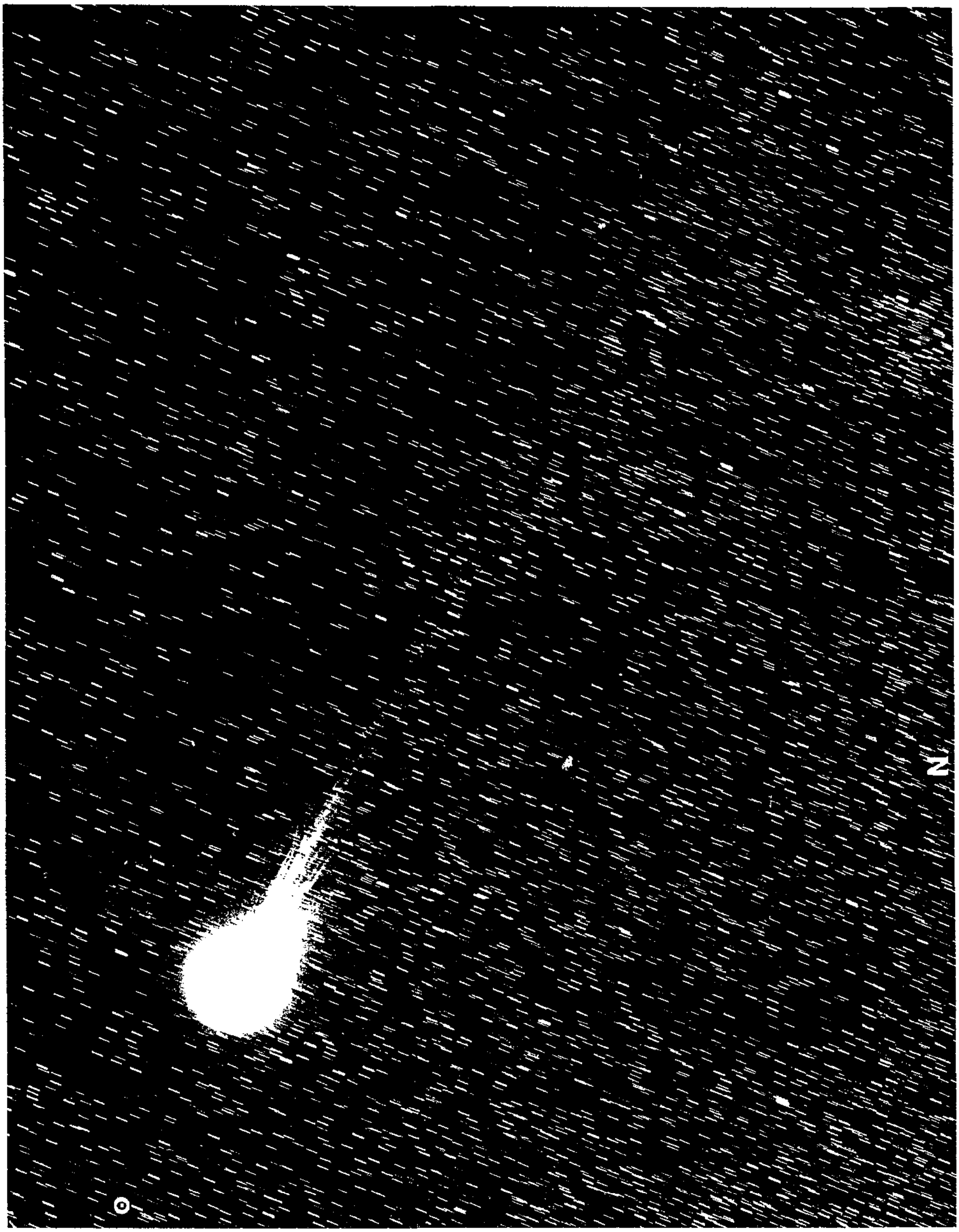

Fig. 4. Schmidt exposure of comet P/Swift-Tuttle on 26 November 1992: north and Sun direction are indicated by symbols **N** and **o**, respectively. The field shown is 1.7 × 2.2 deg. The diagonal streak through the tail at the comet head is due to an emulsion failure. Exposure: 18.15-18.38 UT on IIIaJ plate without filter.

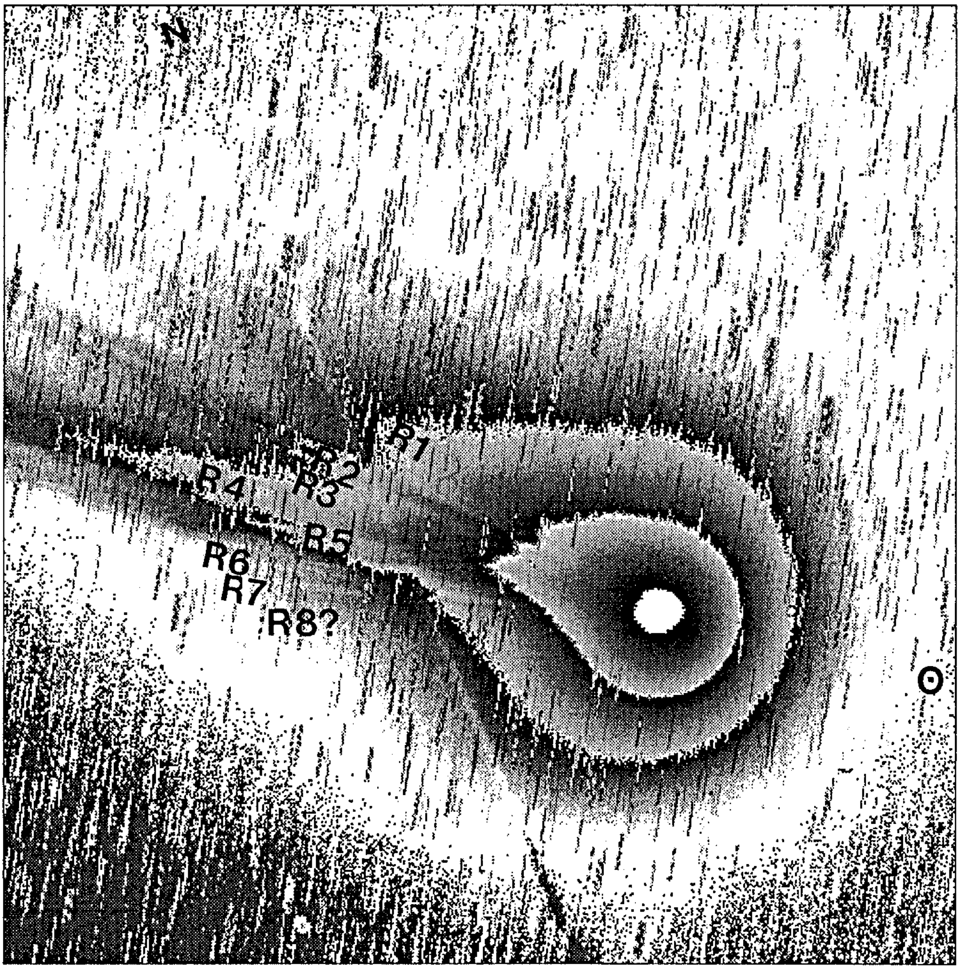

Fig. 5. Comet head detail of the PDS scan of P/Swift-Tuttle from the Schmidt plate of 26 November 1992 (see Chapter 4): north and Sun direction are indicated by symbols **N** and **o**, respectively. The field size is 30 × 30 arcmin. The diagonal streak through the tail at the comet head is due to an emulsion failure. Tail rays are indicated by **R1-R8**.

sky, plate edge reached) pointed into anti-solar direction (at position angle (PA) of 51 deg close to the comet head). At the edge of the coma many sharp tail rays (see Figures 4, 5) and some diffuse streamers (see Figure 6) can be identified in the tailward and sunward coma hemisphere, respectively. The central and most prominent ion tail streamer is over 500000 km wide (in the PDS scan) and contains many filaments and other substructures downstream of the cometary head (see Figure 4). Particularly apparent is a wavy pattern starting at about $1.9 * 10^6$ km behind the coma. At approximately the same distance the PA of the tail diminished slightly by about 5 deg. Similar phenomena were observed in the plasma tails of several other comets. The physical nature of these large-scale features is not really

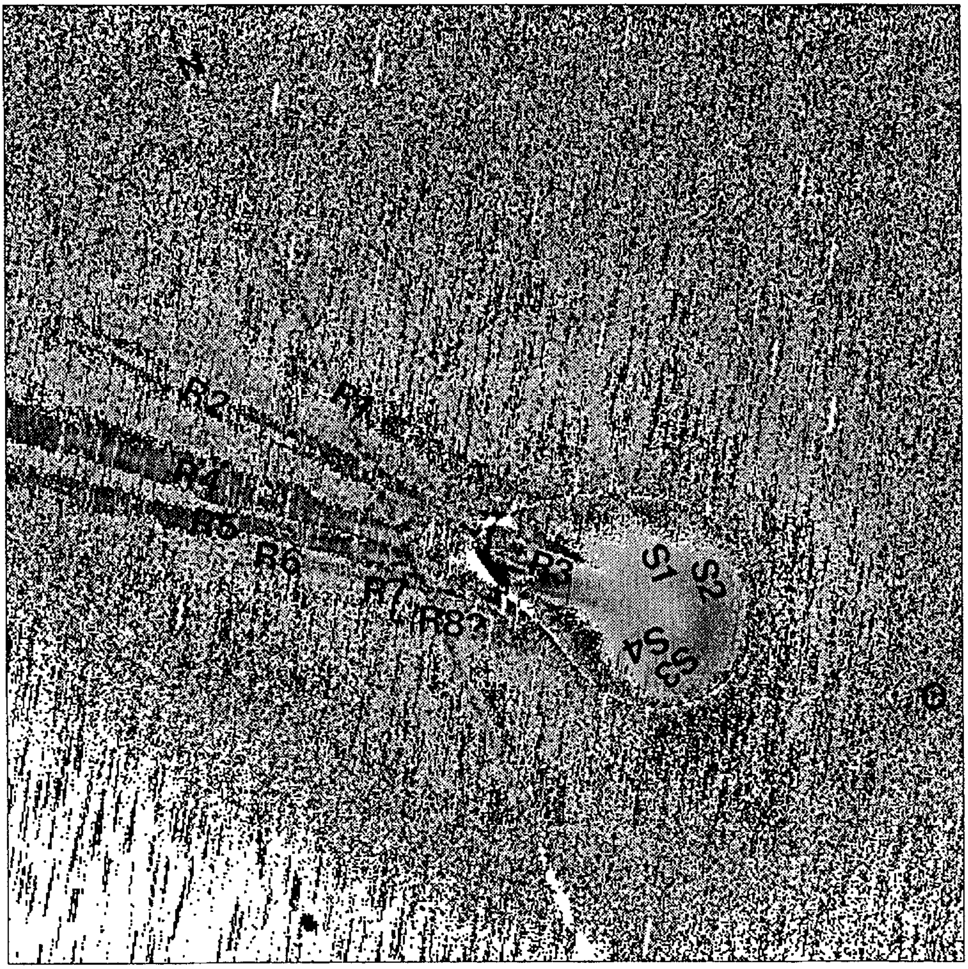

Fig. 6. Unsharp-masking result of the comet head as seen in Figure 5: Tail rays are indicated by **R1-R8**, head streamers by **S1-S4**. For structure enhancement the PDS frame was logarithmized and divided by a smoothed version (smoothing area: 20 × 20 pixels). North and Sun direction are indicated by symbols **N** and **o**, respectively. The field size is 30 × 30 arcmin. The diagonal streak through the tail at the comet head is due to an emulsion failure.

clarified, but may be related to sudden changes in the solar wind flow direction (for a more detailed discussion of the various explanation scenarios see Ip and Axford, 1982, and Fernandez and Jockers, 1983).

Due to the green and shorter wavelength range of this plate, only few dust signatures can be found in the images. In particular the dust tail is not at all easily detectable. Amateur exposures on TP2415 film (Kammerer and Möller, 1994) indicate a possible diffuse dust tail at about 35 deg PA. According to own calculations using a Finson-Probstein code for dust tail modelling (Beißer, 1990) the dust tail of P/Swift-Tuttle should have been confined within PA range from about 35 to 10 deg. In our Schmidt exposure three weak and broad streamers are seen over a much fainter and diffuse background in the sector where the dust tail of the comet should appear. It is noteworthy that these streamers become less sharp with decreasing position angle, i.e. for larger inclination relative to the projected radius vector of the comet from the Sun. The dust tail modelling shows that the eastern streamer can be due to dust which was released within the last month before the observing date. The synchrones of the dust particles with emission times after late October 1992 converged – partly due to projection effects – in this PA range. This may explain both the diffuse streamer observed around 35 deg and the non-detection of finer emission patterns in the dust tail region which may have traced the nucleus rotation motion. The two other streamers in the dust tail sector may represent dust which was released from the nucleus about two to four months before perihelion transit of the comet. However, there are three arguments for an alternative explanation of these structures: first, the calculated synchrone pattern in this PA range is wider than that around 35 deg. Second, the comet was much further away and certainly less active (at least 4 mag fainter according to visual brightness estimations) by the time when this dust pattern should have been released from the nucleus. Both effects together should have weakened the dust tail signatures around PA = 20 to 10 deg which is not found in our observations. The third reason is an alternative explanation for these streamers as extended coma plasma features projected into the dust tail region (see Chapters 3.4 and 3.5).

3.3. TAIL RAYS

In the Schmidt exposure of 26 November 1992 (see Figures 4, 5, 6) several rays of the plasma tail of P/Swift-Tuttle can be identified. In Figure 4 at least one pair of sharp and bright tail rays can be found on each side of the central ion tail at the comet head. They extend to several 10^6 km from the nucleus (which is assumed to coincide with the brightness center in the coma). Four weaker rays emerge from the coma between PA 60 and 75 deg and can be seen to typically 10^6 km from the nucleus. Since these rays are all very similar in appearance (straight, narrow and neddle-like) and are located outside of the dust tail region, we consider them as of plasma origin.

The CCD image (see Figure 3), taken at the 1.2m telescope through a CO^+ filter just 30 minutes after the Schmidt plate, displays more details of the plasma rays in the inner coma. The rays are already detectable in the unprocessed image, but they can be better localized after structure enhancement by adaptive Laplace filtering (Boehnhardt and Birkle, 1994). At least 8 narrow tail rays are to be seen which originate from the inner coma. A cross-check of the CO^+ structures with those of other filter exposures taken at the 1.2m telescope within about 20 min from the CO^+ frame confirms the reality of these tail rays in the inner coma: they are present at the same locations in the coma and are particularly pronounced in the R, B and CO^+ images. The BC dust filter image contains mainly one strong spiral jet which is emitted by an active region on the nucleus (for further details see Boehnhardt and Birkle, 1994) and continues into a fading dust streamer in the tail region of the coma. Diffuse streamers are found in the north-west and south-east coma quadrants. These features partially coincide with the so-called brightness excess areas (BEA) described in Boehnhardt and Birkle (1994). They are seen in all filter bands used during this night, but are much less apparent in the BC dust filter. As discussed in our earlier paper, a gaseous or plasma origin of these phenomena is very likely.

It would be very interesting to verify whether the rays and streamers seen on the Schmidt plate can be related to corresponding structures of the CCD coma images of the same night. Positive identifications would further improve the physical interpretation of the phenomena, in particular their plasma nature and from which region in the coma they originate.

We measured separately (with an accuracy of 1-2 deg) the PAs of the tail rays as identified in the Schmidt exposure (Figures 4, 5 and 6) and in the CO^+ CCD image (Figure 3) of 26 November 1992. It should be noted that in the Schmidt image the central coma (within a radius of about 100000 km) is almost saturated and cannot be used for structure analysis. Fortunately, the central brightness peak in the coma, which represents the nucleus position, can be localized as a point of reference. On the other hand, the CCD frame shows only the inner coma within a maximum nuclear distance of about 240000 km. Therefore, the PAs of the tail rays in the Schmidt exposure and in the CCD frames are measured in two distinct distance ranges from the nucleus. Besides the PAs of the ray orientation in the Schmidt plate, we estimated also the PAs and nuclear distances of their footpoints in the inner coma (see Figure 3b) as well as the nuclear distance of the detection limit of the rays (mostly from the Schmidt plate; see Figure 4). Table III summarizes the results for the tail rays in both image media. In that table the rays are identified by capital letter R followed by an integer (in ascending order with increasing PAs).

Evidently, the PAs of the tail rays in the Schmidt exposure – which are best seen between 500000 to 1000000 km projected nuclear distance - closely match the PAs of the inner coma rays – which are detectable from about 20000 to 240000 km projected nuclear distance. Hence, we conclude that the rays with equal or very similar PAs in the inner (CCD) and outer (Schmidt) coma are virtually identical, i.e. they represent the same plasma feature in the ion tail. Hence, the combination of Schmidt and CCD images allows to trace these ion structures from the distant tail into the near-nucleus region. Their footprints end on the tailward side of the inner coma between 21000 and 35000 km projected nucleus distance. This interpretation implies that the PAs of the tail rays essentially did not change within about 30 min, the time span between the Schmidt and CO^+ CCD exposure used for the measurements. A check of PA changes of the tail rays in our other CCD exposures of the same night also supports this assumption within the uncertainties. In the Schmidt and CCD exposures of P/Swift-Tuttle from 25 November 1992 significant changes in the ray and central tail pattern can be seen as compared to the situation on 26 November 1992. Two multiple rays emerge from the comet head almost symmetrically and next to the tail axis (inclination of about 5 deg to tail axis). There are indications for weak head streamers seen also in this Schmidt exposure. As on 26 November 1992 the northern tail features appear brighter than the southern ones.

As can be found in Figures 3–6 and from Table III the majority of the tail rays appears as close pairs, i.e. for instance R1, R2, R4 and R6. For R2 the "pair splitting" – whether physically real or as a projection effect – is depicted in Figure 3. Besides these close pairs also wider pairs of major tail rays can be identified: R2 and R3 as well as R4 and R6. Both pairs split in the inner coma (see Figure 3b and Table III). The close double rays of R1 and most likely also the wider pair R7 and R8 resemble individual rays which evolve from the near-nucleus region as separate features. No clear sign of "ray splitting" can be found, although from our images it cannot be totally excluded. Rays R4 and R5 – which appear also as split – represent the central plasma tail from which the curly distant tail originates (see Chapter 3.2 and Figure 4). R4 itself is pointing exactly into anti-solar direction. The opening angle of the cone of tail rays R1-R8 is about 35 deg, with R4 lying right in the cone axis. On each side of the central tail (R4 and R5), there are three major tail rays: R1-R3 on the northward side, R6-R8 on the soutward side. Generally, the northern tail rays are brighter and extend further from the nucleus than the southern ones. The width of the ray channels is of the order of 10000-15000 km as measured in the outer coma region (see Figures 4, 5, 6).

3.4. HEAD STREAMERS

The four streamers in the outer coma of comet P/Swift-Tuttle (see Chapter 3.2 and Figure 6) appear weaker, broader and much more diffuse (typically 50000 km wide) than the tail rays. They are indicated by symbols S1-S4 in Figure 6 (the Schmidt exposure of 26 November 1992). The streamers appear in two pairs (S1+S2 and S3+S4) which are oriented rather symmetrically to the plasma tail axis. S2 and S3 clearly evolve from the sunward coma side.

Inspection of the CO^+ CCD image of the same night reveals four brightness excess areas (BEA; indicated as B1-B4 in Figure 3) which are located also in the sunward coma hemisphere, but much closer to the nucleus (about 20000-40000 km projected nucleus distance). Again, one pair of BEAs (B1+B2) is north, the other pair (B3+B4) is south of the approximate axis of symmetry, i.e. the Sun-comet line. The BEAs in the north-western quadrant are brighter than those in the south-eastern one. There are only very marginal indications of a connection (brightness brigde!) between B2 and B3.

The BEA geometry B1-B4 is very similar to that of the head streamers S1-S4. However, our data do not provide a firm evidence for a possible interrelation between both coma features. In particular, no connecting structures between BEAs

TABLE III

Position angle and extension of plasma tail rays in the inner and outer coma of comet P/Swift-Tuttle on 26 November 1992

Tail Ray Designation	PA Schmidt (deg)	PA CCD (deg)	Starting Point PA/Distance (deg)/(km)	Detection Distance (km)	Remarks
R1	37	35 39	7/25000 15/28000	$1.1 * 10^6$	2 separate tails on CCD to at least 220000km diffuse on Schmidt plate, merged? dust tail overlapping?
R2	42 43	42	46/32000	$\geq 5.0 * 10^6$ $\geq 5.0 * 10^6$	double on Schmidt plate, pair split at PA = 42 deg and 550000 km in coma, R2 and R3 split at PA = 38 deg and 88000 km in coma
R3	48	47	46/32000	$1.2 * 10^6$	R2 and R3 split at PA = 38 deg and 88000 km in coma
R4	50 52	52	55/35000	$\geq 7.2 * 10^6$	double on Schmidt plate, merged downstream in tail, next to anti-solar direction, R4 and R6 split at PA = 54 deg and 80000 km in coma
R5	56			$2.1 * 10^6$	split from R4?, no counterpart on CCD frame
R6	59 60	60	55/35000	$1.2 * 10^6$ $1.2 * 10^6$	double on Schmidt plate, R4 and R6 split at PA = 54 deg and 80000 km in coma
R7	64	65	90/21000	$0.8 * 10^6$	marginal on Schmidt plate, R7 and R8 evolve from same coma region or are split, overlap with dust jet close to coma center
R8	72	70	90/21000	$\geq 0.2 * 10^6$	marginal on Schmidt plate, R7 and R8 evolve from same coma region or are split

and head streamers at corresponding PAs in the coma can be found (for instance between B1 and S1).

3.5. DISCUSSION OF THE RESULTS

Our analysis of the Schmidt and CO^+ CCD images of comet P/Swift-Tuttle taken on 26 November 1992 shows that tail rays can be traced from distant tail regions back to the very inner coma, i.e. to 20000-40000 km projected distance from the nucleus. In the case of P/Swift-Tuttle no ray folding effects are observed over time scales of the order of 30 min. However, both the Schmidt exposures on 26 November 1992 and the days before as well as many other CCD frames taken during a one month observing run of the comet (Boehnhardt and Birkle, 1994) confirm a considerable day-to-day variation of the ray pattern. However, our observations do not reveal the three-dimensional structure of the tail rays. Contrary to the tail rays, we were not able to verify a connection between the diffuse head streamers in the outer coma of P/Swift-Tuttle and the BEA substructures in the inner coma, although some similarities (for instance the pair appearance and the PAs) are recognized.

Both tail rays and head streamers are frequently discussed as ion phenomena which are caused by the same physical process (see Fernandez and Jockers, 1983; Ip and Axford, 1982). According to the favoured models, both features may be related to the passage of solar wind discontinuities through the cometary plasma environment. The head streamers may then represent parabolic plasma envelopes which approach the coma from the Sun direction with velocities of about 50 km/s. The smearing due to the relatively high velocity may then explain their diffuse appearance in long exposures like our Schmidt plates. These envelopes are decelerated in the coma to velocities of a few km/s. Because of the reduced velocity they can then be observed as narrow ion rays on the tailside of the comet.

The wavy structures and bending of the main tail on 26 November 1992 may resemble a tail kink due to a sudden change in the solar wind direction. It is noteworthy to mention that the inner tail rays R2 and R6 extend as double rays each to the nuclear distance where the disturbance in the main ion tail starts off. Ray R6 disappears completely in that distance range, while ray R2 becomes very weak, but can still be followed to larger distances.

From our image material it is not clear whether the common distance range for the footprints of the tail rays and the sunward streamers in the BEAs of the inner coma has a physical meaning. It is hard to believe that this formation envelope may be related to the presence of a diamagnetic cavity around the nucleus of P/Swift-Tuttle. Such a cavity was measured in-situ at comet P/Halley (diameter about 10000 km; see Neubauer *et al.*, 1986). Because of the lower gas production rate of P/Swift-Tuttle (Bockelee *et al.*, 1994) such a cavity should have been smaller than that of P/Halley. Spinrad et al. (1994) have found that the H_2O^+ ions in the tail of P/Swift-Tuttle were accelerated at 10000 km nuclear distance (probably already closer to the nucleus). This also argues against the cavity interpretation for the region surrounded by the starting points of the tail rays. At present it cannot be excluded that the ray-less region in the immediate neighbourhood of the nucleus might be an image processing artefact, although in many of our observations the much stronger dust and gas jets can well be detected closer to the nucleus.

4. Concluding Remarks

The nucleus of P/Swift-Tuttle seems to be one of the largest nuclei measured so far (a list of available size determinations is given by Jewitt, 1991, and O Ceallaigh *et al.*, 1995). Absolute brightness of P/Swift-Tuttle was fainter in 1992 (Kammerer and Möller, 1994) than that of P/Halley in 1986 (Green and Morris, 1987) as well as was the gas and dust production of P/Swift-Tuttle below that of P/Halley (Bockelee *et al.*, 1994). This may imply that also the surface area of the active regions on the nucleus of P/Swift-Tuttle (four active spots have been identified in 1992; see Boehnhardt and Birkle, 1994) was not as large as that of P/Halley. The negative result of our coma search in 1994 could either mean that the bare nucleus was detected or that the coma is very much condensed inside the seeing disk of the comet. A clear answer to this remaining ambiguity can be given if more brightness measurements of the comet at larger heliocentric distances become available. A CCD monitoring programme over some 3-5 days should also reveal brightness variations due to the rotation of the (possibly aspherical) nucleus of P/Swift-Tuttle. Modelling of the near-perihelion jets and fan in the coma should allow to determine the rotation axis of the nucleus as well as the distribution of the active regions on the nucleus. These information can then be used to verify whether these regions are no longer illuminated during the outbound journey of P/Swift-Tuttle which may explain the inactive status of the nucleus in 1994. If we really detected the bare nucleus in 1994, comet P/Swift-Tuttle can be observed to at least 20 AU heliocentric distance when it should be around 25-26 mag. This may give us the unique chance to search for distant coma activity as observed for P/Halley at 14 AU from the Sun (West *et al.*, 1990).

The physical nature of the tail rays, the head streamers and BEA substructures as well as of the curved and wavy pattern in the plasma tail of comet P/Swift-Tuttle cannot fully be clarified on the basis of our observations. Our finding of the starting points of the tail rays in the inner coma may need an adequate theoretical interpretation. Also, the meaning of the streamer structures at the comet head as well as of the BEAs in the inner coma is an open issue. Certainly, the evaluation of further coma and tail observations of P/Swift-Tuttle collected by other colleagues may supplement our results and in that way broaden the picture of the plasma phenomena in that comet.

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