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The nuclei of comets 26P/Grigg-Skjellerup and 73P/Schwassmann-Wachmann 3*

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Abstract. The target of the second GIOTTO fly-by, Comet 26P/Grigg-Skjellerup (26P/GS), and the back-up candidate for ESA's ROSETTA mission, Comet 73P/Schwassmann-Wachmann 3 (73P/SW3), were observed to support the interpretation of the in situ experiment results and the preparation of the forthcoming cometary mission, respectively. The main goal was the size estimation of the nuclei through broadband CCD imaging when the comets were far from the Sun (26P/GS: 3.8 AU in September 1993, 73P/SW3: 3.0 AU in December 1994). The nucleus of 26P/GS has an equivalent radius of 1.5 km (for an albedo of 0.04) with a body axis ratio of 0.9 or less (considering other observations possibly just 0.5 or less). The comet was inactive at 3.8 AU outbound and exhibited a slightly bluish V-R colour. Comet 73P/SW3 was smaller than 1.1 km radius (for an albedo of 0.04) before break-up in 1995 and showed solar V-R colour. The nucleus was weakly active at 3.0 AU inbound in December 1994. The gas production rates measured during the perihelion passages of the comets in 1992 (26P/GS) and 1995 (73P/SW3) together with our radius estimations suggest that the nuclei of both comets had a significant crust coverage on their surface.

Key words: comets: individual: 26P/Grigg-Skjellerup – comets: individual: 73P/Schwassmann-Wachmann 3

1. The programme and the targets

With the advent of space missions to comets, short-period comets became the focus point of scientific interest since only this object class is potentially accessible for spaceprobes (within the constraints of a limited financial budget and of a mission profile of less than two decades duration). Although frequently monitored during the perihelion arcs of their orbits a few key parameters of these comets are still widely unknown: the size, shape and rotation, the surface colour and crust, the activity onset of the nucleus. Apart from their importance for the interpretation of the scientific results from in situ experiments of the spacecraft and for the planning of future cometary missions, the good knowledge of these nucleus parameters is also relevant for our scientific picture of comets per se. Only a handful of reliable measurements of the size and the rotation period of comets are published (for reviews see Meech 1998, Jewitt 1998). These observations indicate (but do not prove) that short-period comets have very small nuclei (Meech 1998) of the order of a few kilometers or even less than one kilometer (for example: radius of 0.7 km for 46P/Wirtanen, Boehnhardt et al. 1996; 0.4 km for 46P/Honda-Mrkos-Pajdusakova, Lamy et al. 1996 and Meech & Hainaut 1998). About surface properties like crust coverage and activity onset, our observations and knowledge are even more sparse.

It is therefore not a surprise that all target comets of past and future spacecraft missions were selected without good and accurate knowledge of these nucleus properties and even after the spacecraft visits some of these basic parameters of the objects are still unknown. This holds also for two targets of cometary missions of the European Space Agency (ESA), i.e. Comet 26P/Grigg- Skjellerup (26P/GS), the target for the second comet fly-by of the GIOTTO spacecraft in 1992, and Comet 73P/Schwassmann-Wachmann 3 (73P/SW3) which was the former prime target of ESA's new ROSETTA mission and is now still listed as a back-up object for later launch windows of the mission.

26P/GS: the nucleus radius (between 0.4-3 km) is constrained by radar observations (lower limit radius of 0.4 km; Kamoun 1983 and Kamoun et al. 1996) and ground-based photometry (Roemer 1966, Birkle & Boehnhardt 1992 and references therein, Meech 1998). Sitarski (1992) tried to estimate the body shape and axis ratio of the comet from modelling the non-gravitational forces by a nucleus rotation model with forced precession (prolate ellipsoid rotating around its longer axis, axis

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* Based on observations collected at the German-Spanish Astronomical Center, Calar Alto, operated by the Max-Planck-Institut für Astronomie, Heidelberg, jointly with the Spanish National Commission for Astronomy.

Table 1. Observing geometry of the comets and atmospheric conditions during the observations

Object	Date (UT)	Sun Distance (AU)	Earth Distance (AU)	Phase Angle (deg)	Seeing (arcsec)	Atmosphere
26P/GS	14-18/09/1993	3.82	2.85	5	1.0-1.2	2 nights photometric
73P/SW3	27-31/12/1994	3.03	2.35	15	1.2-1.6	2 nights photometric

ratio of 0.7). The nucleus rotation period is unknown. Only marginal indications exist from ground-based observations for the presence of active regions on the nucleus (Birkle & Boehnhardt 1992, Fulle et al. 1993). Unfortunately, it was not possible to investigate these nucleus properties with GIOTTO since the adequate onbord experiments could not be operated during the fly-by. Gas and dust production rates at the time of the GIOTTO encounter can be found in Jockers et al. (1993), Fulle et al. (1993) and from GIOTTO experimenters (Neubauer et al. 1993, Johnstone et al. 1993). A single set of production rates is also available from the 1987 apparition (Osip et al. 1992). It is noteworthy that OPE data of the coma passage of 26P/GS allow an interesting, but controversial interpretation by multiple jets or nucleus fragments (McBride et al. 1997, Le Duin et al. 1996). Coma lightcurve parameters are given by Muraoka (1996, 1997).

73P/SW3: this comet is much less observed than the GIOTTO target 26P/GS. Lightcurve parameters are given by Marsden (1994), a size estimation (1.2 km radius; Sekanina et al. 1998) of the nucleus is based upon the visual brightness of the central coma condensation given by Baldet (1930a,b) from the 1930 apparition. The comet broke into at least 3 pieces in autumn 1995 (Boehnhardt & Käufl 1995; for a detailed analysis see Sekanina et al. 1998) after it underwent a major outburst in late August and September 1995 as concluded from OH radio observations (Crovisier et al. 1996).

Information on the orbits of both comets (both in the past and for the future) can be found in Belyaev et al. (1986).

Because of their relevance for spacecraft missions and for cometary science we have selected both comets as targets for ground-based CCD imaging campaigns. The goal of the observations was to constrain the size and rotation period, to measure the broadband colours and to assess the activity status of the nucleus while far from the Sun. In the following, we describe the results obtained through our imaging campaigns for 26P/GS in 1993 and for 73P/SW3 in 1994.

2. The observations and the data reduction

The CCD imaging of the two target comets was performed with the 3.5m telescope of the Max-Planck-Institut für Astronomie at the Calar Alto Observatory in Spain. Comet 26P/GS was observed in mid September 1993 about 1 year after its perihelion passage, Comet 73P/SW3 in late December 1994 about 3/4 year before perihelion. Table 1 lists the observing geometry and gives information on the prevailing atmospheric conditions during the observations. Both comets were observed through Johnson V and R filters. The detector, a 1024×1024 pixel Tektronic CCD (maximum quantum efficiency = 90 percent around 650 nm, gain = 3.9 electrons/ADU, read-out noise = 2 ADU) of 24 μm pixel size, provided a 6.93×6.93 arcmin field of view (pixel resolution = 0.406 arcsec) at the f/3.5 prime focus of the telescope. During comet imaging the telescope followed the differential motion of the target. The standard star fields were taken from the list of Christian et al. (1985) and Odewahn et al. (1992).

For Comet 26P/GS, altogether, we could obtain 43 V and R exposures of (in nearly all cases) 1200 s duration each. For the final data evaluation, however, we only used the 23 R and 3 V exposures of the 2 photometric nights of Sept. 14/15 and 16/17. The V images for the measurement of the V-R colour index were always taken immediately after an R exposure. In the case of 73P/SW3, a total of 10 R and 4 V exposures of either 1200 s or 900 s could be taken during the first 2 of the 4 nights indicated in Table 1.

The first steps of the data reductions were bias level subtraction, flatfield division as well as cosmics and bad columns removal. For the absolute photometry the counts of the objects and of the standard stars were measured by aperture integration and sky subtraction in the images (avoiding overexposed stars). The photometric reduction was executed using a computer code which follows the principles described by Sterken & Manfroid (1992). The basic routine was provided by J. Manfroid (University Lieège, Belgium), but was considerably modified and supplemented for the application described (Rainer, 1997).

From the 23 selected R images of 26P/GS, 17 frames could be used for the lightcurve analysis, the rest was discarded because of high statistical errors due to star blends of the comet image or high sky background. For 73P/SW3 all 10 R filter exposures were taken for the lightcurve inspection although their intrinsic quality is not as good as the data for 26P/GS are. Additionally, relative photometry between the comets and reference objects was exercised using stars and galaxies which were visible in all frames of a single observing night.

For the deep coma search, all available R exposures of the respective comet (without star blends) were aligned to have the peak maximum of the object at the same pixel and were thereafter coadded. For the improvement of the signal-to-noise ratio (S/N) in the low level magnitude range, pixel smoothing (3×3 pixels) and linear rebinning by a factor of 0.625 was applied to the coadded images. Finally, we obtained coadded images of 9.5 h total integration time for Comet 26P/GS and of 3.5 h

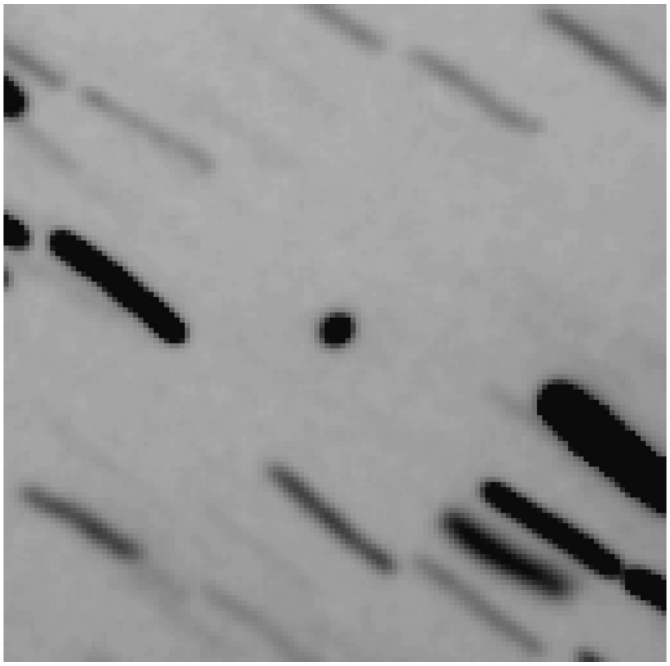

Fig. 1. Coadded image of Comet 26P/Grigg-Skjellerup. In total 9.5 h of broadband R filter exposures from the period 14-17/9/1993 are coadded. North is up, East to the left, the field of view is 51 × 51 arcsec.

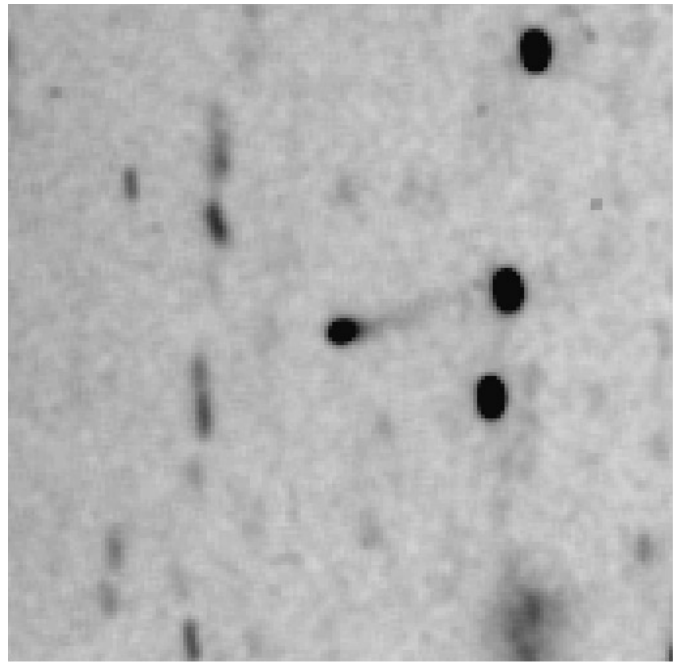

Fig. 2. Coadded image of Comet 73P/Schwassmann-Wachmann 3. In total 3.5 h of broadband R filter exposures from the period 27-30/12/1994 are coadded. North is up, East to the left, the field of view is 70 × 70 arcsec.

total integration time for Comet 73P/SW3 (Figs. 1 and 2). The detection limit of a potential coma and tail signal could be improved to 27 mag/arcsec^2 for 26P/GS and to 25.5 mag/arcsec^2 for 73P/SW3. The image processing was executed using the MIDAS (Munich Image and Data Analysis Software) package of the European Southern Observatory ESO.

3. Results

In the following, we describe for each comet separately the results obtained from our CCD image analysis and photometry. The (equivalent) radius was calculated from the mean (averaged over the available measurements) filter brightness of the comets following the standard equation as given for instance in Huebner (1992; Eq. (2.1), Sect. 2.2.1). The albedo was assumed to be 0.04, for the (linear) phase angle correction of the radius value a darkening coefficient of 0.03 mag/deg was used. The summary of the results is given in Table 2. R(1,1,0) and V(1,1,0) are the R and V magnitudes of the comets at 1 AU Sun and Earth distance and for 0 deg phase angle. The V-R colour of the Sun is 0.55 mag.

3.1. 26P/Grigg-Skjellerup

At the time of our observations (i.e. when the comet was at about 3.8 AU from the Sun) 26P/GS was inactive when moving outbound after the 1992 encounter with the GIOTTO spaceprobe of ESA. This is concluded from the star-like appearance of the comet and from the absence of a weak coma in our coadded image (Fig. 1). The equivalent radius of the nucleus is 1.45-1.50 km with a good agreement in both measured filters R and V (Table 2). The V-R colour is slightly bluish as compared to the Sun (Table 2). The lightcurve of the nucleus does not seem to be properly sampled by our observations (Fig. 4). However, a minor variability of (at least) 0.1 mag peak-to-peak is noticeable. This would correspond to a small-to-large-axis ratio of 0.9. The detected variability of the nucleus brightness seems to be real since it is larger than the 1-sigma uncertainty of the photometric magnitudes (and it is very similar in both the absolute and the relative photometry data). From the temporal development of the observed brightness variation we conclude that a rotation period of less than 0.5 days would hardly match our (partial) lightcurve of the nucleus.

3.2. 73P/Schwassmann-Wachmann 3

In late December 1994 73P/SW3 was at 3 AU solar distance moving inbound to its next perihelion passage in autumn 1995. It had already developed a weak dust coma and tail as can be seen in our images (Figs. 2 and 3). Hence, the photometry of the comet may no longer give the light reflected at the surface of the nucleus alone, but it is contaminated by some light from the coma (which was estimated not to exceed about 20 percent of the total light from the object). Therefore, the radius value of 1.1 km (which was determined using the uncorrected flux) represents an upper limit for the nucleus size (almost identical in R and V; Table 2). The V-R colour of 73P/SW3 was solar (within the errors of our photometry; Table 2). The R filter brightness increased by about 0.25 mag within 1 day (Fig. 5). However, our observations do not indicate whether this was a secular (due

Table 2. Photometry, colour, radius, rotation and activity status of 26P/GS and 73P/SW3. Errors are 1 sigma.

Object	R R(1,1,0) (mag)	V V(1,1,0) (mag)	Radius R Radius V (km)	V-R R Variability (mag)	Activity Status
26P/GS	21.60 ±0.07	22.02 ± 0.12	1.44 ± 0.05	0.42 ±0.10	inactive
	16.27	16.69	1.51 ± 0.09	≥0.1	
73P/SW3	21.57 ± 0.05	22.05 ± 0.23	1.10 ± 0.03	0.48 ±0.17	coma and tail
	16.85	17.33	1.13 ± 0.12	≥ 0.3	detected

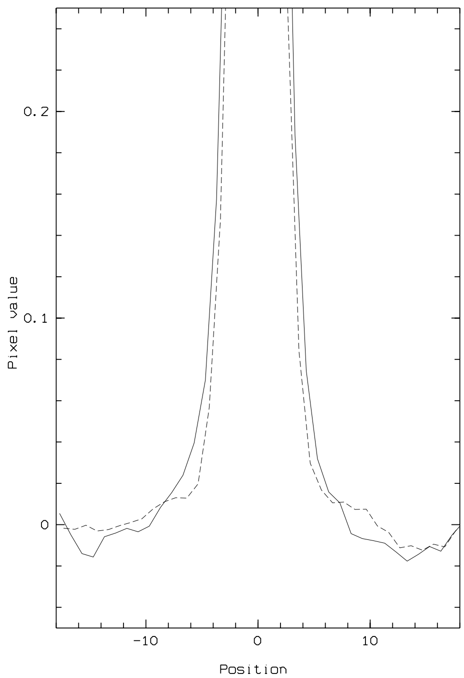

Fig. 3. Comparison of 73P/SW3 and star image profile. The R filter images of P/SW3 were aligned once centered on the comet and once on the stars and were in each case co-added. From the resulting two sum frames subimages of the comet (comet image) and of a star similar in brightness (star image) were extracted. The comet and the star image were scaled to the same maximum (pixel value = 1) and minimum brightness (average pixel value = 0 on the neighbouring sky background) and profile cuts were taken (for the comet perpendicular to the position angle of the tail direction, for the star perpendicular to the trail direction). The plot shows the comet (continuous line) and the star profile (dashed line) close to the sky background. Obviously, a faint and very condensed coma was surrounding the nucleus of the comet.

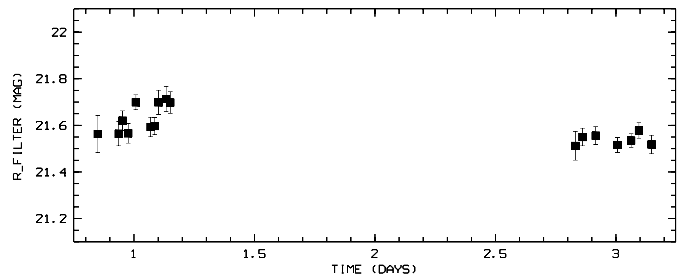

Fig. 4. The R filter lightcurve of Comet 26P/Grigg-Skjellerup during the observing period. Time zero point is 15/09/1993 0UT. Error bars for 1 sigma.

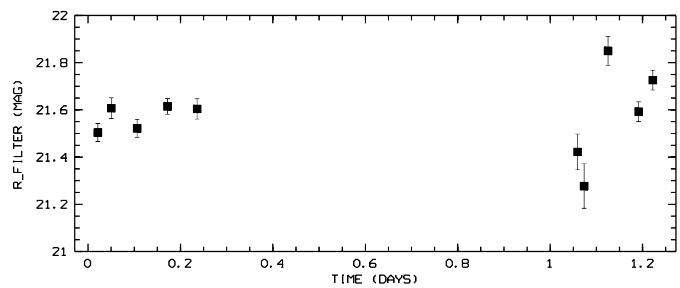

Fig. 5. The R filter lightcurve of Comet 73P/Schwassmann-Wachmann 3 during the observing period. Time zero point is 28/12/1994 0UT. Error bars for 1 sigma.

to a general brightness increase) or a periodic (due to nucleus rotation) effect. The coadded images of the comet show a weak coma and a short tail (Figs. 2 and 3). The estimated radial diameter of the coma was 11800 km, the lateral one was 8300 km. The tail had a length of 13200 km and pointed to a position angle of 281 ± 2 deg (measured North over East) which is in agreement with the position angle of the extended radius vector from the Sun (282 deg). Apart from this tail structure, the comet showed a very symmetric and smooth coma, and no coma structures typical for insulated active regions on a rotating nucleus (like jets, fans, shells) could be detected. Although no direct proof by simultaneous spectroscopy exists, we can assume – based upon the similarity of the cometary images in R and V and upon the weakness of coma gas emission bands in these wavelength ranges – that the observed coma and tail represented mostly the dust distribution around the comet.

4. Discussion

Obviously, both comets, 26P/Grigg-Skjellerup and 73P/Schwassmann-Wachmann 3, have a very small size as compared to other periodic and non-periodic comets (see Meech 1998). In fact, they are among the smallest nuclei of short-period comets and only 46P/Wirtanen (Boehnhardt et al. 1996) and 45P/Honda-Mrkos-Padajowskaja (Lamy et al. 1996) seem to be even smaller objects.

Our equivalent radius estimation of 1.5 km for 26P/GS is larger than the one determined by radar observations (Kamoun 1983, Kamoun et al. 1996), but it is smaller than the values deduced from other ground-based CCD photometry by Birkle & Boehnhardt (1992; 2-3 km) and by Meech (1998; 2.9 km). Unfortunately, GIOTTO measurements could not be used for the size estimation of this nucleus. Considering the uncertainty of the radii from the CCD photometry, we conclude that this nucleus is either of non-spherical shape with a maximum axis ratio (small-to-large) of 0.5 and/or it has a rather variable surface albedo (the large crust coverage of the surface – see discussion below – makes this scenario less likely). The latter axis ratio is in disagreement with the one determined by Sitarski (1992; 0.7) from an analysis of the non-gravitational forces on the cometary orbit. The larger axis ratio (0.9) determined from our lightcurve of the comet could be due to a different viewing geometry of the effective nucleus cross section. In summary, although the exact value of the axis ratio may still be debatable, it is very likely that Comet 26P/GS has a non-spherical nucleus. The rotation of the nucleus seems to be longer than 12 h, a conclusion supported by our photometry of the nucleus lightcurve. The observed coma fans (Birkle & Boehnhardt 1992, Fulle et al. 1993) are at least in qualitative agreement with a fast rotation period of the order of one day or less. Using our value for the nucleus size (1.5 km) and model calculations for the gas release from water ices (Huebner 1992), one can conclude that the water production rate observed during the GIOTTO encounter period ($6\text{-}7\times10^{27}$ molecules/s: see Neubauer et al. 1993 and Jockers et al. 1993) required only about 5 percent of the surface being active. At least some – if not a major amount – of this activity must have been concentrated in an active region which produced the coma fan during the last two apparitions (Birkle & Boehnhardt 1992, Fulle et al. 1994). Therefore, a large crustification of the nucleus of 26P/GS has to be assumed. The nucleus crust and the different illumination geometry of the comet by the Sun may also explain the absence of a weak coma in our September 1993 (post-perihelion) observations. In conclusion, Comet 26P/GS has a very small, non-spherical and highly crusted nucleus which may be typical for a very evolved and old periodic comet. Nevertheless, the measured slightly bluish V-R colour does not comply with our general picture of red colour gradients for evolved cometary nuclei. The nucleus fragments which are hypothesized from OPE observations onboard GIOTTO (McBride et al. 1997) must have been beyond the detection limit of our combined data of 9.5h total integration (the detection limit of 27 mag corresponds to about 200m equivalent radius) or already outside of the field of view of our detector (6.9 arcmin corresponding to 860000 km projected distance at the distance of the comet).

Our 1.1 km radius for 73P/SW3 gives only an upper limit for the size of this comet (because of the light contamination from the weak coma and tail). It is, however, in surprisingly good agreement with the radius value which is obtained from the visual brightness estimations of the central coma condensation (considered to represent the nucleus) made by Baldet during the close approach of this comet to Earth in 1930 (Baldet 1930a,b). Sekanina et al. (1998) calculated a radius of about 1 km from this rather coarse visual photometry of the comet. Obviously, 73P/SW3 had a very small nucleus already before it broke apart in 1995 (Boehnhardt & Käufl 1995; Sekanina et al. 1998 and references therein). If the sub-nuclei can be detected after the dust and gas emission of the split fragments has ceased, it may be possible to measure and compare directly – for the first time ever – the size of the parent body with those of its fragments. Shortly before break-up in 1995 the comet was hyperactive (Sekanina et al. 1998) as can be concluded from the observed OH production rates (Crovisier et al. 1996). The effective radius to support this activity is more than 2 km (Sekanina et al. 1998) which is at least a factor 2 larger than our upper limit. The former authors suggest that evaporating icy grains may have contributed a significant amount of OH in the outburst phase before the break-up of the comet. Considering the fact that during the past apparition the lightcurve of the comet followed the normal development until the outburst in August/September 1995 and assuming a proportional down-scaled water production rate as compared with the outburst level (which was 22.2×10^{28} molecules/s; Crovisier et al. 1996), one arrives at a nucleus radius of 0.2 km which could produce the typical perihelion activity if 100 percent active. This would mean a crustification of the surface of around 96 percent or in other words only about 4 percent (minimum) of the surface area were needed to be active in order to support the typical perihelion activity of this comet. The nature of the variability in our comet photometry of 73P/SW3 is not known (secular brightness increase or effects from the nucleus rotation). At the time of our observations the comet had already started the pre-perihelion activity. One month later, the comet appeared about 2 mag brighter (own unpublished observations of 29 January 1995). However, in mid 1994 the comet could not be detected with the 3.5m Calar Alto telescope (again own unpublished observations). Hence, the small coma diameter in December 1994 may indicate that the activity onset was not very strong and/or that we observed the comet in a very early state of gas and dust production, i.e. during activity onset. In summary, 73P/SW3 is another example of a small cometary nucleus, but it may be different in its crustification and gas and dust emission since it developed from a (likely) very crusted into an hyperactive object. Its V-R colour is very similar to that of 26P/GS and does not show any reddening effect (as expected for old and evolved objects). Finally, our conclusions on the possible crustification of the nucleus can be jeopartized by the two main assumptions used for our calculations, i.e. that the effective nucleus radius is close to our measured upper limit and that the water production rate near perihelion scales according to the visual brightness of the comet. If this is not the case, the nucleus of P/SW3 would be more active and with less crust coverage.

5. Concluding remarks

Our observations have demonstrated that the second target of the GIOTTO spacecraft, Comet 26P/Grigg-Skjellerup, has a 1.5 km radius nucleus of slightly bluish colour. They clarified the question of the nucleus size of this comet which represented a so far unknown parameter in the interpretation of results from the GIOTTO in situ experiments. Comet 73P/Schwassmann-Wachmann 3, although only a back-up target for ESA's ROSETTA mission, may have gained scientific attractiveness, since its nucleus is split and one can expect that the new surface areas exhibit fresh and widely unprocessed cometary material to sunlight. This could be an enormous advantage and gain for the surface science experiments of a spaceprobe which focuses on the exploration of the pristine cometary matter from the origin of the solar system. On the other side, such a mission could have a higher risk for hazardous encounters with large (blocksize or larger) bodies which remain for a very long time in the neighbourhood of the split nuclei completely undectable from ground. As a striking fact and in contrast with our general expectation of reddened cometary nuclei both comets show solar or slightly bluish V-R colours although their nuclei were covered by a large surface crust. Fresh layers of dust fall-out from the latest perihelion activity cycles could be responsible for the neutral (i.e. solar) colour of both nuclei.

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