An interesting application of redshifted molecular absorption lines in general comes from the fact that the excitation of the molecules might be dominated by the cosmic microwave background radiation. For dense gas this requires relatively high redshifts, but for diffuse gas, where collisions between molecules are infrequent, this can occur at intermediate redshifts. This latter situation seems to apply to the absorbing gas towards PKS1830–211. For the HCN, HCO^+ and HNC molecules we have derived an excitation temperature of 6–8 K. This is significantly higher than the expected temperature of the cosmic microwave background radiation, T_{CMB}, which at a redshift of $z = 0.89$ should be 5.16 K[1], but since these lines are heavily saturated they only give an upper limit to T_x. The unsaturated lines of CS, N_2H^+ and $H^{13}CO^+$, which directly give T_x, have an excitation temperature of only ~ 4 K. This is less than the expected temperature of the cosmic background radiation, but given the 3σ errors, the excitation temperatures are still consistent with a T_{CMB} at $z = 0.89$ of 5.16 K. The very low values of T_x show that the excitation of the molecular lines is dominated by the cosmic microwave background radiation and, given our observational uncertainties, we can derive a conservative upper limit to T_{CMB} of 6.0 K. Detection of more molecular absorption-line systems at similarly high, or higher, redshifts offers the possibility of observing the evolution of T_{CMB} as a function of redshift.

Although the excitation temperature of the molecular lines is low, the actual kinetic temperature of the gas may be considerably higher. The abundance ratio of the isomeric molecules HCN/HNC acts as a thermometer of the kinetic temperature; when this ratio is ~ 1, the gas has a T_k of approximately 15–20 K, whereas if the ratio is well in excess of 1, the temperature is 50–100 K. This effect stems from the way molecules are formed through gas-phase reactions. For our absorption lines towards PKS1830–211, we estimate the kinetic temperature to be around 16 K.

[1]In the big-bang theory, the temperature of the microwave background radiation scales as $T_{CMB} = T_{bg}(1+z)$, where T_{bg} is the temperature at $z = 0$.

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The Break-Up of Periodic Comet Schwassmann-Wachmann 3: Image Documents from La Silla Telescopes

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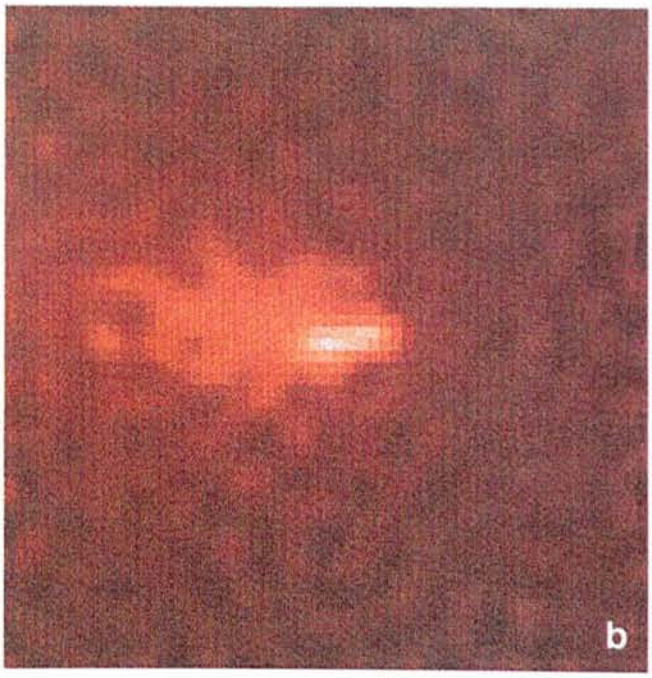
1. Science with an Ordinary Comet

Until recently comet 73P/Schwassmann-Wachmann 3 (hereafter SW3) was considered a rather ordinary comet and as not being worthwhile a dedicated observing programme. Therefore, not much more than orbital elements and brightness estimates were available when the European Space Agency ESA became interested in this object as a potential target for the next cometary mission ROSETTA. SW3 belongs to the family of Jupiter comets a group of comets with orbits substantially and repeatedly affected by Jupiter's gravitation. Indeed, it was Jupiter that brought SW3 into its present orbit: two encounters in 1965 and 1978 changed the perihelion distance and inclination of the comet's orbit from 1.02 to 0.94 AU and from 17.3 to 11.4°, respectively (Belyaev et al., 1986).

But what is the scientific interest in observing SW3 nowadays? The driver was ESA's selection of the comet as a back-up target for the ROSETTA mission. The design of the scientific experiments onboard ROSETTA and the planning of the mission operations require the knowledge of basic physical properties of the comet, such as the nuclear size, rotation, activity profile, chemistry, the production rates of gas and dust, etc. Addressing these mission-related parameters on the basis of observations, one simultaneously contributes to the characterisation of SW3 as a member of the Jupiter family comets. It is important to learn about the similarities and diversities among comets and comet families and to establish a classification scheme for these solar-system objects which are believed to represent the most pristine and unaltered remnants of the solar system nebula. In that way it may be possible to constrain the formation history and conditions of our planetary system and furthermore the development of comets since their formation in the interplanetary and interstellar environment around the Sun.

2. The Prelude Observations

As a potential ROSETTA target, comet SW3 was monitored more thoroughly than usual. Almost monthly, broadband filter imaging of SW3 was performed by



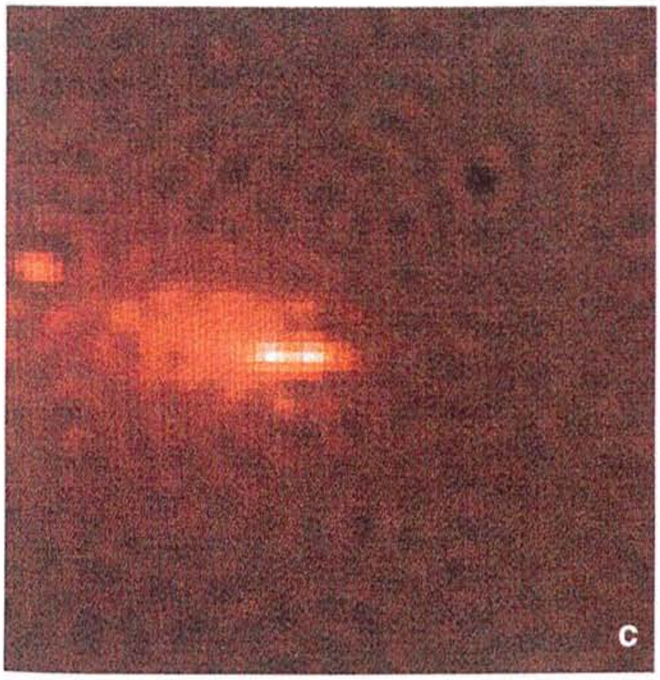


Figure 1a: SW3 on October 27, 1995. The 20-sec B-filter exposure was obtained by J. Manfroid (Liège) with the Dutch telescope at ESO-La Silla. This subframe of the central coma region was deconvolved by Richardson-Lucy algorithm. North is up and east to the left, the field of view is 22 × 22 arcsec.

Figure 1b: SW3 on November 27, 1995. The 120-sec B-filter exposure was obtained by K. Reinsch (Göttingen) with the 2.2-m telescope at ESO-La Silla. This subframe of the central coma region was deconvolved by Richardson-Lucy algorithm. Image orientation as in Figure 1a, the field of view is 19 × 19 arcsec.

Figure 1c: SW3 on December 2, 1995. The 120-sec R-filter exposure was obtained by J. Storm (ESO) with the Danish 1.5-m telescope at ESO-La Silla. This subframe of the central coma region was deconvolved by Richardson-Lucy algorithm. Image orientation as in Figure 1a, the field of view is 27 × 27 arcsec.

H. Boehnhardt and K. Birkle from late December 1994 until late June 1995 using telescopes at ESO La Silla and at the Calar Alto Observatory. During that period of time the comet behaved normally: a coma and tail were detected in late January 1995 when the comet was at 2.8 AU solar distance and developed as expected. The comet was brightening gradually until at least August 20, 1995, when it was estimated by a Japanese amateur astronomer at magnitude 13.

The first indication that something unusual happened to SW3 came from J. Crovisier and collaborators (1995, 1996) who detected a much higher OH production with the Nancay radio telescope on September 8–12, 1995, compared with that on September 1–5, 1995. Amateur astronomers reported the comet to be about 5 mag brighter than expected in late September 1995 (around 8 mag). This elevated coma brightness continued and still increased during October 1995 (SW3 then being brighter than 6 mag, i.e. more than 200 times brighter than normal at this distance). However, at that time the reason for this strong and continuous outburst of the comet was unclear.

3. The Break-Up of the Comet

A regular observing programme on SW3 by the first two authors of this paper was scheduled at ESO-La Silla for December 12–14, 1995. By means of simultaneous observations using the NTT plus EMMI for the visual wavelength range and the 3.6-m telescope plus TIMMI for the mid-IR range the gas and dust content in the comet should be characterised. Alerted by the reports on the SW3 outburst, the authors approached colleagues with a request for additional images of the comet before the beginning of their own observing campaign. As a result, exposures of SW3 were taken between late October and early December 1995. All these observations (including those taken after the break-up was detected – see below) had to be made under rather difficult conditions: since the comet's elongation from the Sun was only between 43 to 56°, these images were taken through high air masses (elevations from 35 down to 12°) and the daily observing window was rather short.

4. The ESO Image Gallery of the Break-Up

The break-up of the comet was detected by Boehnhardt and Kaeufl (1995) during their simultaneous observations at the NTT and 3.6-m telescopes. The R filter and 10-micron images revealed a total of four fragments in the coma (A, B, C, F), but only three at either wavelength region (see Fig. 2). Two fragments (A and C), i.e., those at the extreme ends of the almost linear chain, seemed to be present both in the visual and IR wavelength range. The third companion, B in the visual and F in the infrared, were clearly different. Hence they produced significant signal levels only in the specific wavelength regions. The three-day observing run also revealed an increase in the distance between the fragments A, B and C and short-term variations in the brightness of their innermost regions.

The continuously increasing separation between the pieces A-C was confirmed by the follow-up observations scheduled on a short notice for the NTT on 7 and 31 January 1996 (see Fig. 3). By that time the fragments clearly had their own comae and tails embedded in a common sheath of material and the relative brightness of the companions may have stabilised.

Inspection of the earlier images of SW3 taken before the break-up detection in mid-December 1995 confirmed an extensive coma development. The central brightness peak in the coma was elongated in the east-west direction. However, applying the Richardson-Lucy deconvolution algorithm to the central coma region, the elongated peaks seen on November 28 and December 1–2, 1995 could be resolved into two separate fragments (see Fig. 1b,c). Evidently, the distance and the position angle of the two pieces changed during this 5-day interval. Despite all our efforts, we were unable to resolve the central coma peak in the late October to early November images (see Fig. 1a). However, the deconvolved images may indicate the presence of separate fragments already by that time.

5. Break-Up Scenarios

The ESO images of comet SW3 provide a unique documentation of the evolution of the SW3 fragments after the break-up. Using position measurements of the three condensations A, B, C, it is possible to derive solutions for the break-up sequence (for a theoretical background see Sekanina, 1982). An initial analysis of the ESO data (supplemented with those of other observers) performed independently by Sekanina and Boehnhardt & Kaeufl (1996) indicated a two-step break-up sequence, with the fragments A and B breaking off as a single body from the fragment C around October 24, 1995, while A and B themselves broke apart on December 1, 1995. In the meantime some more measurements became available and the earlier ones were remeasured in order to improve the position accuracy and to determine the intrinsic uncertainty of the values. Based upon these new data, improved solutions for the separation sequence show B to have split from C before A separated from C, both events in late October and early November 1995 (Sekanina, private communication). One can exclude that the outburst of SW3 observed in September 1995 coincided with the break-up of the nucleus (Sekanina et al., 1996). Instead, we agree with Sekanina (1996) and Crovisier et al. (1996) in their conclusion that the outburst commenced more than one month before the nucleus splitting. Thus, the increased activity apparently represented a prelude to the dramatic break-up of SW3.

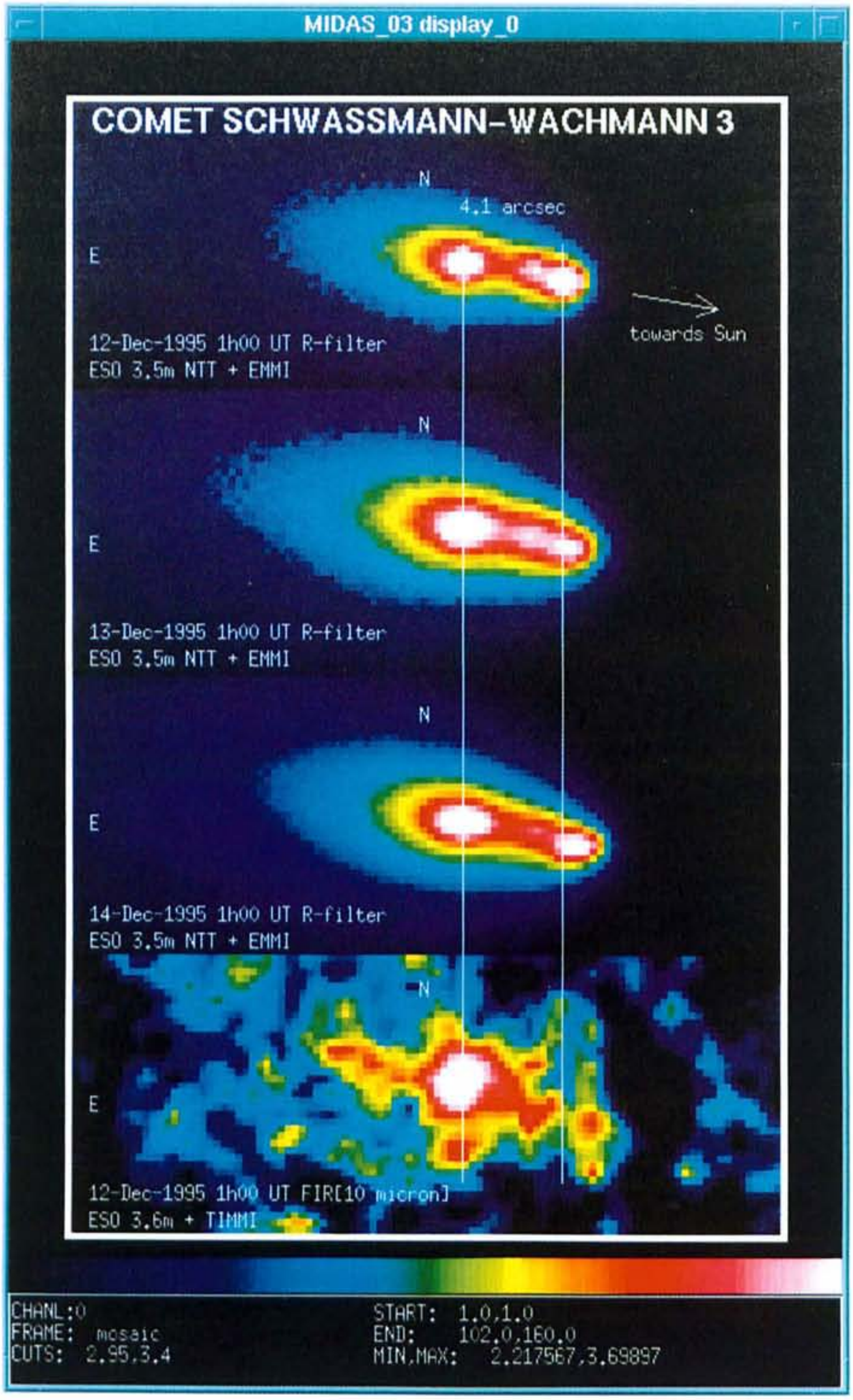


Figure 2: SW3 on December 12–14, 1995. The series of images was obtained by H. Boehnhardt (Munich) and H.U. Kaeufl (ESO) at the ESO NTT with EMMI and at the ESO 3.6-m telescopes with TIMMI. The upper three subimages show the relative motion and brightness variability of fragments A–C as seen in the visual wavelength range. The lower subimage gives the 10-micron view of the inner coma of SW3. Image orientation and scale is given in the figure, no image deconvolution applied.

The existing observations do not provide a clear indication on the physical processes involved in the SW3 nucleus fragmentation. Possible scenarios are:

(1) The disruption of the surface crust over a large area caused by erupting pressurised gas under the surface layer

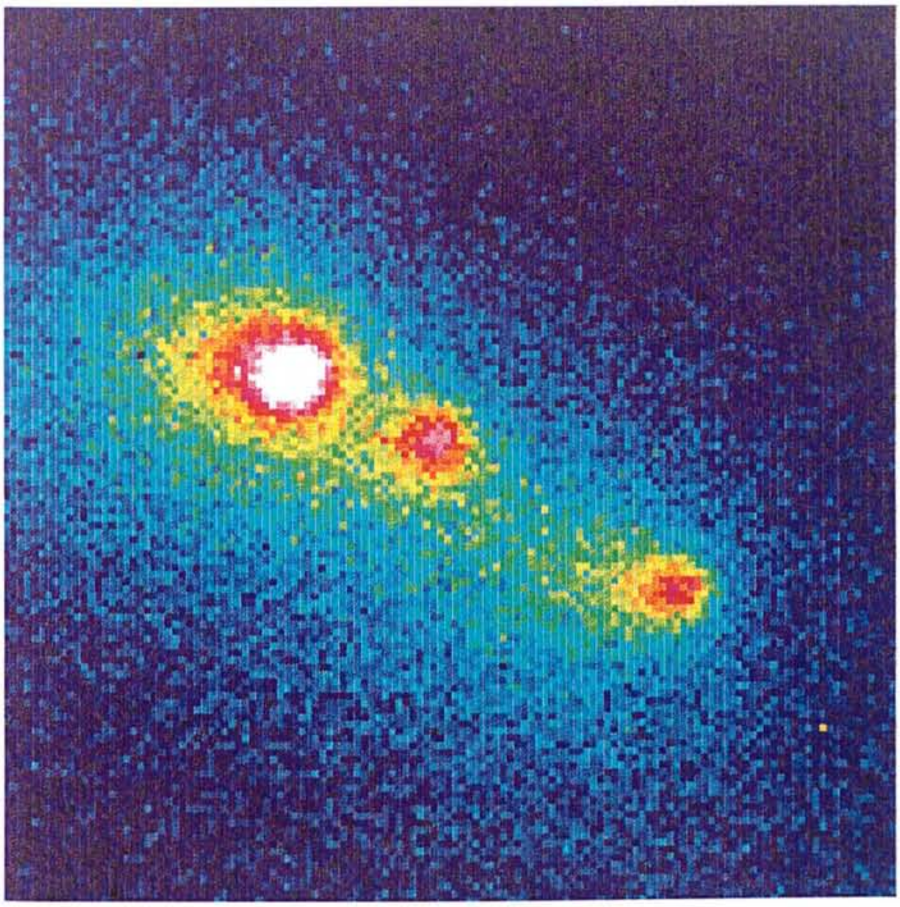


Figure 3: SW3 on January 31,1996. The 300-sec R-filter exposure was taken by P. Goudfrooij (ESO), H.U. Kaeufl (ESO) and H. Boehnhardt (Munich) with the ESO NTT plus EMMI. Image orientation as in Fig. 1a, the field of view is 34 × 34 arcsec, no image deconvolution applied.

of the nucleus as the comet approaches the Sun (the outburst of SW3 happened just 2–4 weeks before perihelion). Subsequently, the new and highly active regions release a large amount of gas and dust into the coma which simultaneously erodes the internal structure of the weakly bound comet body. As a result, major pieces can separate from the nucleus.

(2) A spin-up of the nucleus due to reaction forces from the outgassing results in new cracks in the surface due to a centrifugal stress in the nucleus. Hence, the gas and dust release increases which may both weaken the internal structure of the cometary body and may further accelerate the nucleus rotation. When the critical rotation rate is reached (order of a few hours; Sekanina, 1982), the comet begins to disintegrate.

(3) The impact of a major body on the nucleus severely damages the surface crust. The follow-up scenario of such an event resembles that described under (1). The impactor may have been a gravitationally bound fragment of the nucleus itself. Such companions are suspected to remain undetected in the proximity of the nucleus for very long times.

The enormous OH production observed in September and October 1995 (Crovisier et al., 1996) and the small nucleus size (our own unpublished observations indicate a nucleus radius of 1–1.5 km, see also Birkle and Boehnhardt, 1996) required almost the whole nucleus surface being active during the pre-splitting outburst. This constraint may be somewhat relaxed if one assumes a significant production of material from minor nucleus fragments released during the outburst. The detection of further fragments (for instance our IR fragment F or any of the additional ones reported by other observers, see IAU Circular 6301) could be evidence for the existence of numerous fragments around the nucleus.

6. SW3 and ROSETTA

The recent outburst and fragmentation of the SW3 nucleus may initiate new considerations about the role of the comet for the ROSETTA mission. Since this spacecraft project is very ambitious from the operational and scientific point of view (for instance continuous monitoring of the comet from circumnuclear orbit over about one year and two surface science packages to be landed on the nucleus), the splitting of SW3 presents new risks but also has some attractive aspects. The risks are the increased danger for the ROSETTA spacecraft from the debris around the nucleus and – even worse – the disappearance of the comet if a break-up should result in the object's disintegration. The positive aspect of this event is the implication that – if the nucleus of SW3 survives – fresh material from the nucleus interior becomes easily accessible on the surface. It is in the affected regions of the surface that the original and unmodified ingredients of the pre-solar nebula can be found (rather than on the largely evolved and processed surface crust of periodic comets that did not split). This perspective makes comet SW3 – at the moment – much more attractive for addressing fundamental questions of the solar-system formation by *in-situ* experiments than any other ROSETTA target.

7. Concluding Remarks

The splitting of SW3 in 1995 was another example of how brittle cometary nuclei are. Unlike in most previous events, however, the break-up of SW3 is well documented by high-quality ground-based observations, many of them carried out at ESO. SW3 represents an excellent candidate for a comprehensive analysis of cometary fragmentation, which could lead to a better understanding of the disintegration processes involved in the evolution of comets. An important unresolved key question both for the continuing break-up modelling and for the ROSETTA mission is the survival of the SW3 fragments. It will be addressed by further observations when the comet becomes visible again after its conjunction with the Sun.

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