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IMAGING OF VERY DISTANT COMETS: PRESENT EXPERIENCE AND FUTURE EXPECTATIONS

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SUMMARY AND DISCUSSION OF OBSERVATIONS

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Imaging of very distant comets: Present Experience and Future Expectations

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Abstract Exploratory observations of a small number of comets at very large heliocentric distances have been made with the 3.5 m NTT at the ESO La Silla observatory. Very deep CCD images were obtained of fields around LP comets Schuster (1975 II) at heliocentric distance 31.3 - 31.5 AU, Bowell (1982 I) at 23.6 - 23.8 AU, Shoemaker (1984 XV) at 17.1 - 17.7 AU, as well as P/Halley (1986 III) at 14.0 - 16.2 AU. We briefly discuss the special data acquisition and reduction methods which were used to reach the deepest possible limiting magnitudes, and also some of the basic problems encountered in this type of work.

During this study, P/Halley was found to have suffered a major outburst in late 1990 at heliocentric distance 14 AU, i.e. too far from the Sun for this to be explained by water ice sublimation. In April 1992, the image of P/Halley (at 16.2 AU) was superposed on a small cluster of faint galaxies, but careful subtraction of the contribution from the galaxies still allowed the detection of a luminosity excess of V = 25.5 ± 0.6 at the predicted position of the comet. This experience illustrates a major problem in future observational studies of very distant solar system objects. None of the other comets were detected at the 2σ level, corresponding in the best cases to a limiting magnitude of about $V = 27.2$. This result indicates the absence of recent, major outbursts in these comets and permits to derive rather stringent upper limits of the size of their nuclei.

1. Introduction

Improved observational techniques, together with better telescope and detector technology, have recently opened a new window towards the outer solar system. It is now possible with ground-based telescopes to follow comets to never-before attained heliocentric distances and to monitor their behaviour beyond Saturn. A small number of observational programmes have been started along these lines, notably at Hawaii and at La Silla. In this paper, we present a preliminary report on exploratory observations of extremely distant comets. In view of the extreme faintness of these objects, special observational and reduction techniques have been necessary. A more comprehensive paper is being prepared for publication (Hainaut et al., 1993).

The very distant comets observed during the present programme were selected according to the following criteria:

1. the heliocentric distance is larger than 15 AU, that is much beyond the region where the traditional processes of water sublimation can drive the cometary activity;
2. the present position is known to an accuracy of a few arcseconds or better, ensuring secure identification of the image;
3. the galactic latitude is larger than 15° , in order to avoid extreme crowding problems, and
4. the size of the nucleus is expected to be greater than or about equal to that of Halley.

The last requirement is of course quite uncertain, because it is based on photometric measurements made at much smaller heliocentric distance while the comet was active. The expected V-magnitudes of these objects are typically in the 25–29 range, but with a very large uncertainty.

During our observing periods in 1992, the best candidates in terms of position and expected brightness were comets P/Halley (at $R = 16$ AU), Shoemaker 1984 XV (17 AU), Bowell 1982 I (24 AU) and Schuster 1975 II (31 AU).

2. The Observations

The limiting magnitude needed to detect these comets or at least to establish useful upper brightness limits must be very deep, i.e. at least 27 mag or fainter in the V band. This implies long integrations of the order of 1 hour at a telescope of the 4-metre class. Good seeing is of course equally important, as the sparse light is then concentrated in a smaller area on the detector with a corresponding improvement in the signal-to-noise ratio, which varies with the 4^{th} power of the seeing disk diameter.

Four half-nights in the period November 1991 – April 1992 were allocated to this programme on the ESO 3.56m New Technology Telescope (NTT) at the European Southern Observatory, La Silla, Chile. The first one was lost because of technical problems at the beginning of the night (parasite light in the camera) and inferior seeing (around 1.6 arcsecond). The other three runs were all successful. The three first runs were performed using the SuSI camera ("Superb Seeing Imager"), with a pixel size of 0.26 arcsecond on a Tektronic CCD (1024^2 pixels, used in 2×2 binned mode). During the last run, for technical reasons we had to use one of the cameras of the ESO Multi-Mode Instrument (EMMI) at the other Nasmith focus of the NTT. with the somewhat large pixel size of 0.37 arcsecond (on a 2048^2 pixel Ford Aerospace CCD). All images were taken through a standard V filter. Table 1 shows the log of the observations. During each run, several photometric standards were obtained as well as the usual twilight flat-fields, bias and dark exposures.

The sky background is much brighter ($V_{sky} = 21.5$ mag/sq. arcsec) than the objects observed ($V \sim 25$ - 27) and the main source of noise is therefore the poissonian fluctuations of the sky, which are proportional to the square root of the number of electrons trapped in the CCD, while the other sources of noise (CCD read-out, dark current...) are negligible in this case. This allowed us to split the total exposure time

Comets		Date (UT)	R (AU)	Δ (AU)	Exposures #	Total (sec)	Seeing ($''$)	Limiting V Magnitude (S/N=2)
1986 III	**P/Halley**	6 Apr 92	16.2	15.7	13	8100	1.45	26.4
1984 XV	**Shoemaker**	2 Nov 91	17.1	17.0	10	4800	0.95	26.0
		1 Dec 91	17.7	17.1	3	1440	1.20	26.1
1982 I	**Bowell**	16 Oct 91	23.6	22.6	18	5900	1.85	24.2
		2 Nov 91	23.7	22.7	12	3600	0.78	27.0
		1 Dec 91	23.8	23.2	10	4800	1.05	27.2
1975 II	**Schuster**	16 Oct 91	31.3	30.6	11	3300	1.65	25.3
		2 Nov 91	31.4	30.7	6	1800	0.90	26.4
		1 Dec 91	31.5	30.9	8	2880	0.86	27.1

Table 1: Log of Observations

into many shorter integrations, without adding any significant noise to the data. This procedure is advantageous for several reasons. Firstly, by giving small random offsets to the telescope between each of the short exposures, the object will always fall on different pixels; this avoids any systematic effects due to the sensitivity and geometry of the individual pixels. Secondly, the NTT unfortunately is not yet able to perform blind tracking at offset speeds and thereby to follow accurately a moving object over longer periods. Keeping the exposure time short ensures that the trailing of the object will remain small as compared to the seeing. Thirdly, short exposures are much safer: if a technical problem should occur, only a few minutes of integration time will be lost, while the loss of a longer exposure will be much more painful. On the other hand, excessively short exposures would mean a waste of valuable observing time, since each CCD read-out takes up to 2 minutes. In practice, we decided to take 10 to 20 exposures, each of 5 to 15 minutes duration.

3. Reduction techniques

The reduction method has to be very well considered, and must be optimized in order to extract the maximum information about the very faint objects which is contained in the raw data. In particular, special care must be taken to preserve as well as possible the S/N-ratio of the weak image throughout the process by reducing the influence of all sources of additional noise.

The first steps are the usual electronic bias and dark current subtraction, then the bad columns are interpolated over and the cosmic events are filtered out by means of the common MIDAS procedures. The bias and dark current levels for the used CCD chips were found to be very stable both in space and time, so they were considered just as constants.

Optimal flat-fields are then built, which will correct the spatial sensitivity variations while introducing as little noise as possible into the data. First, all available frames, including both scientific and twilight ones, are normalized and combined by median pixel-by-pixel averaging into one high-S/N frame. From this frame, another is then made which contains the low-frequency spatial variations only; this is done by median filtering over large areas, e.g. 10×10 pixels. By subtraction remains a high-S/N map of the pixel-to-pixel sensitivity variations. For each series of scientific frames covering the same field (i.e. of the same comet), a low spatial frequency flat-field is produced in the same way, i.e. by median pixel-by-pixel averaging of the corresponding, normalized frames, followed by area median averaging. The resulting frame is then multiplied with the above mentioned high-S/N, high-frequency flat-field frame to produce the optimal flat-field for that particular series of scientific frames.

Next, the sky background is removed from each frame by using an iterative, spatial median filtering in combination with a mask, which does not damage the objects. This automatic procedure is slow, but very efficient; it has been thoroughly tested and found to be safe even for the faintest objects.

The individually cleaned frames are then re-combined to form the final frame, representing the total of the acquired exposure time. Accurate offsets between consecutive frames of the same field are obtained from the positions of several field stars. The frames are re-binned so that the pixels of all of them exactly match before the final addition.

For each field, three re-combined frames are generated. In the first one, the stars are centered so that they appear point-like. This frame will show the faintest non-moving objects, in particular galaxies in the field. The comet is trailed over $\Delta T v/p$ pixels, where ΔT is the time interval (sec) between the beginning of the first exposure and the end of the last one, v is the motion (arcsec/sec) of the comet, and p is the pixel size (arcsec). In this frame, the comet will usually not be visible.

In the second re-combined frame, the motion of the comet is taken into account and the light from the comet will here be concentrated within the area of the seeing disk, while the stars will be trailed. This frame is used for the identification of the comet, as well as for photometry and astrometry.

The third re-combination is the opposite of the second frame, in the sense that we now shift the frames according to a motion equal to that of the comet, but in the opposite direction. On this frame, the stars will have trailed images which are exactly similar to those in the second frame, but in the opposite direction and the comet will be trailed over a distance twice as long as in the first frame. As all objects, other than the comet, have exactly the same intensity distribution in the third frame as in the second, a subtraction of the two will show the comet, if it is visible at all.

In what follows, we will refer to three re-combined frames as the "stars", "comet" and "anti-comet" frames, respectively.

The re-combined frames are photometrically calibrated by means of some of Landolt's deep standard fields. The standard stars are typically around magnitude 15-17, that is much brighter than the objects. The extrapolation over many magnitudes is of course a matter of concern, especially in view of the possibility of CCD non-linearities, recently reported in the literature, e.g. by Magain et al. (1992). This problem must be further studied when very deep photometric sequences become available.

The precise position of the comet in the "comet" frame is interpolated according to appropriate methods from secondary astrometric standards taken from the Palomar and ESO/SRC Schmidt survey plates, calibrated with 20–40 PPM stars. In some cases, it was necessary to use third order astrometric standards, because no star in the CCD field was bright enough to be visible on the Schmidt plates. In these cases, additional wide-field CCD images were used to link the plates to the deep comet frames.

The final step is the identification of the comet. In the best case, it will be directly visible. Some image enhancement processes (median filtering, binning, smoothing...) may eventually be used in this connection. Near the limiting magnitudes of this study, a considerable fraction of the frame is covered by images of faint galaxies. If the predicted position of the comet fall on one or several of these, their contribution will have to be carefully removed, see below.

It should be noted that the subtraction of the "anti-comet" from the "comet" frame formally introduces a photometric error. There is some intensity in the comet trail in the "anti-comet" frame at the position of the point-like comet image in the "comet" frame. When they are subtracted, some intensity is removed from the point-like comet image and the resulting image is therefore weakened. However, in the "comet" frame, the object is concentrated in the seeing disk, i.e. $\pi S^2/4p^2$ pixels, where S is the seeing FWHM (arcsec). In the "anti-comet" frame, the light from the comet is spread over approx. $2\Delta TvS/p^2$ pixels, and the relative flux which is subtracted from the comet image is therefore $\pi S/8\Delta Tv$. With typical values for these parameters, e.g. $\Delta T = 2$ hours, $v = 6$ arcsec/hour, $S = 1$ arcsec, the relative error is of the order of 3% only. This is negligible when compared to the photometric error caused by the increased noise of the sky backgrounds of the two frames. For a comet with a high signal-to-noise ratio, this error must be taken into account. However, this method will obviously not be used if the comet is clearly visible !

4. Results

4.1 P/Halley

None of the comets in this study was found to be "clearly visible". Unfortunately, the position of comet P/Halley is right on top of the trails of several faint galaxies. The contribution of these galaxies was removed by subtracting the "anti-comet" frame from the "comet" one. As the trail of these two images match perfectly (cf. Section 3), the light from the galaxies is efficiently subtracted. The main problem of this method is that the seeing conditions may slightly change during the observations. In that case, the subtraction leaves small residual images; this is especially well seen on the images of the brighter stars in the frame.

The resulting frame has a magnitude excess in a region slightly larger than the seeing (2 arcseconds), right at the predicted position of P/Halley, which is not an artefact of the "anti-comet" frame subtraction. Even with a resulting signal-to-noise ratio of only half the one of the original frame, this magnitude excess is statistically significant (2.8 σ). The position, the aspect of the image and its statistical significance lead us to consider this as an actual detection of comet Halley, at mag-

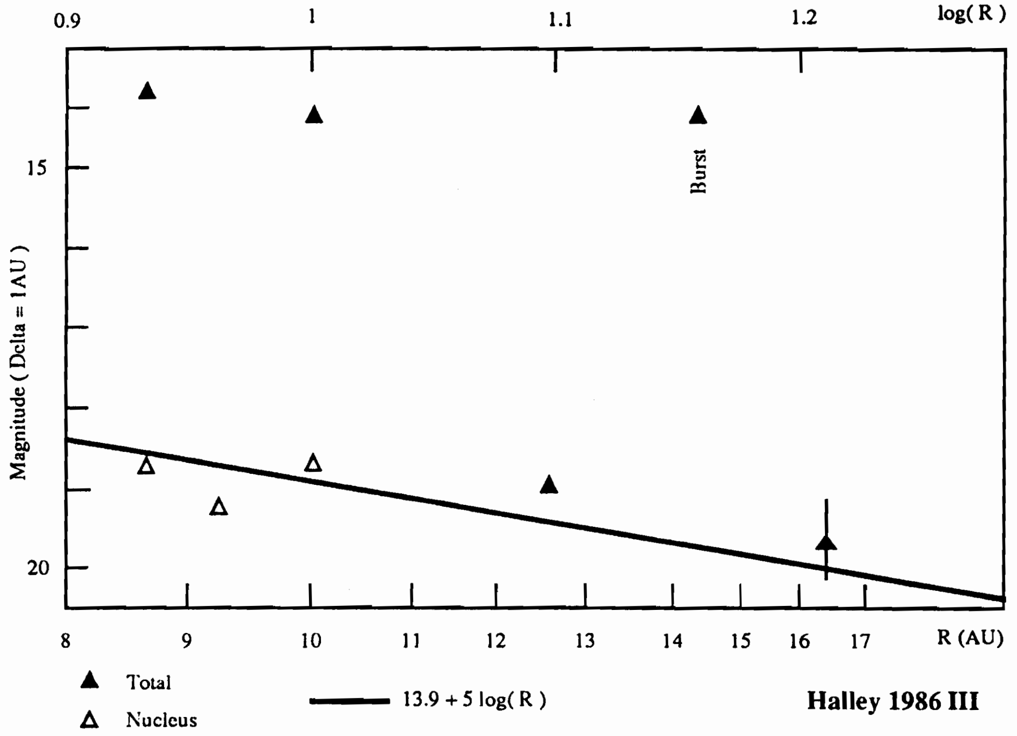

Figure 1: Photometric measurements of comet P/Halley at large heliocentric distances, normalized to the geocentric distance $\Delta = 1$ AU. The solid symbols are total V magnitudes; open symbols represent the nuclear magnitude after subtraction of the coma. The line is the predicted nuclear magnitude.

nitude $V = 25.5 \pm 0.6$.

In Fig. 1 we show the most recent measurements of comet P/Halley at large heliocentric distances (solid symbols). The lines correspond to the predicted magnitude for the bare nucleus. At $R = 8.5$AU (West and Jørgensen 1989) and $R = 10.1$AU (West 1990), a coma was still visible; its contribution was removed, and the resulting nuclear magnitudes are represented by open symbols. At 12.5 AU, the comet was observed as an unresolved point light source (West et al. 1991), with no visible coma. A small intensity excess (0.45 mag) in the four-night average magnitude as compared to the predicted magnitude of the bare nucleus was interpreted as the contribution of a faint, unresolved coma. At 14.5 AU, the comet was found to have suffered a major outburst (West et al, 1991). The evolution of the coma during the observations in the period February – April 1991 showed that the outburst must have begun rather suddenly around Dec. 17, 1990. The April 1992 measurement at 16.2 AU indicates that the coma resulting from the outburst had then completely dispersed. The predicted V magnitude for the bare nucleus was 25.9, i.e. within the error of the measured magnitude.

4.2 Comets Bowell, Shoemaker and Schuster

For the three other comets, observed during the present programme, the described image enhancing techniques and eventual galaxy subtraction revealed some possible candidate images around the 2σ level or higher. However, either the measured position did not coincide with that predicted for the comet, or no corresponding image was found on the frames from another night. It is therefore not possible to confirm the detection of any of these objects.

The limiting magnitudes were evaluated from the sky background statistics and also by extrapolation from several faint objects in the frames; there was good agreement between the values. The deduced limiting magnitudes which are listed in Table 1 correspond to the 2σ level for point-like (i.e. seeing limited) objects. This is a reasonably realistic limit, as we know the accurate position of the comets and also have at least one other frame for confirmation.

Comet Bowell 1982 I has already been observed at large heliocentric distances (Meech & Jewitt 1987). At $R = 11.0$ and 13.6 AU, the comet had a large, faint diffuse coma, which was slowly expanding at a constant rate. No nucleus or central condensation was observed. The corresponding magnitudes as well as some previous ones (from ICQ) are shown in Fig. 2. The straight line corresponds to a $V = V_0 + 2.5 \log R^4$ law and has been drawn through the observed points in order to give an idea of the possible behavior of the comet. At $R = 23.8$ AU, the coma has completely dispersed or has become too faint to be observed. The nucleus is not visible in our frames. The open symbol corresponds to the upper brightness limit ($V > 27.2$) which we obtained on December 1, 1991.

Comet 1984 XV Shoemaker was apparently detected at $V = 23.3$ on December 2, 1991 at a time when the motion was very small and the corresponding position was reported in MPC 20071. Unfortunately, a more detailed analysis showed that the image belonged to a star very near the predicted position and which was weakly visible in less deep control frames of the same field obtained later. This clearly illustrates the need to verify supposed comet detections independently on separate nights.

Comet 1975 II Schuster has been successfully observed at heliocentric distances out to $R = 9.74$ AU, when its B magnitude was around 19.5. Some further attempts were made at $R = 11.16$ to 13.07 AU, using the 3.6m telescope at La Silla with photographic plates. Only upper limits were established (at ~ 22.5, which was the very faintest limit achievable with the technology then available). These results are described in West (1982). The present non-detection implies that the comet is largely inactive, and that the nucleus is too small to be detected.

4.3 Radii of the comets

We have converted the upper limits for the brightness of the comets into upper limits for the size of the nucleus. We used an albedo of 0.03, that is the mean value for small phase angles which is in good agreement with the pre-perihelion absolute magnitude ($V = 13.92$) and the size of the nucleus as measured by Giotto, which is equivalent to a sphere with 4.7 km radius (cf. Keller 1990). The derived radii are listed in Table 2. It is seen that the radius of P/Halley, within the accuracy, is in good agreement with the Giotto measurements.

These maximum radii are unexpectedly small, and suggest that a real detection would have made if it would have been possible to reach 1-2 magnitude deeper. None of the radii can be much larger than that of P/Halley and none of them are found to

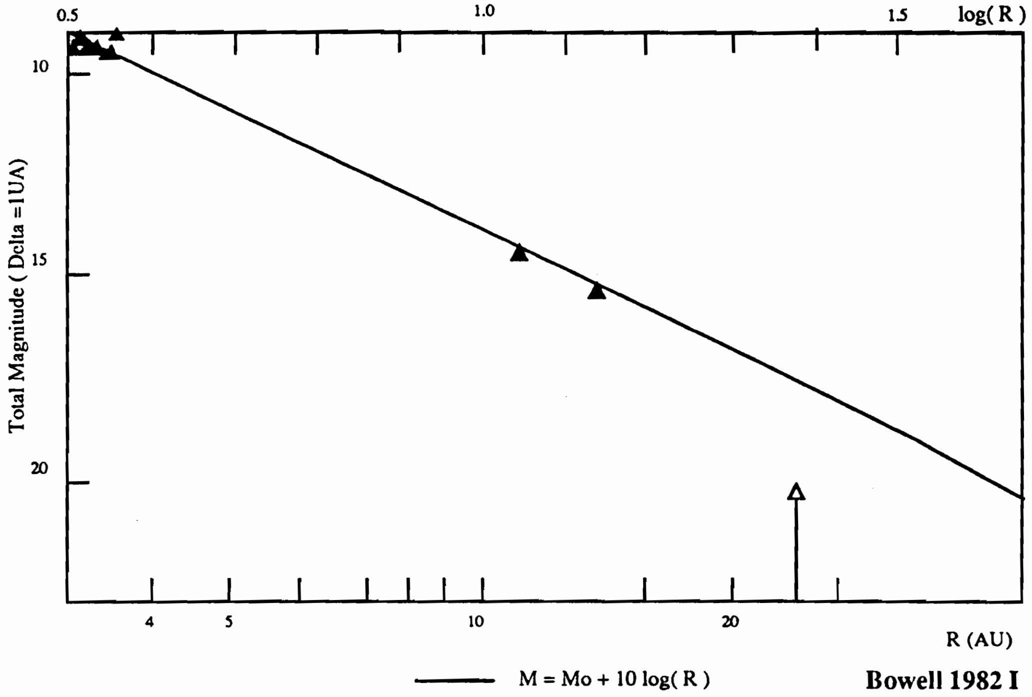

Figure 2: Photometric measurements (normalized to $\Delta = 1$AU) of comet Bowell 1982 I at large heliocentric distances. The solid symbols are total V magnitudes; the line is just a R^4 law passing through the points.

Comet	Date	Magnitude	Radii(km)
Shoemaker 1984 XV	1 Dec 91	>26.1	<4.7
Bowell 1982 I	1 Dec 91	>27.2	<5.8
Schuster 1975 II	1 Dec 91	>27.1	<9.2
Halley 1986 III	6 Apr 92	25.5±0.6	$3.6 < r < 5.9$

Table 2: Limiting magnitudes and nuclear radii

be "giant comets", even though they were very active and intrinsically bright near perihelion. This may indicate that on some comets a larger fraction of the nucleus surface is active than was the case for P/Halley. The three LP comets observed by us are dynamically new comets, passing through the inner Solar System for the first time and their surface crust may be different from that of P/Halley in terms of thickness and composition.

5. Other Objects in the Frames

These deep frames may contain very useful information about other objects than the comets for which they are obtained. In view of the substantial observing time invested in a programme like the present one, it seems reasonable to make at least some effort to extract also the information which has recorded for these.

5.1 Background Galaxies

Since we observed fields at high galactic latitude in order to avoid star crowding, these frames also show very distant galaxies; indeed, most images fainter than about V = 22-23 belong to this class. Around magnitude 27, the number of background galaxies is very large and they cover a significant fraction of the entire field.

The probability that the comet image will be temporarily superposed on one or several galaxy images is correspondingly high. In this paper, the solution to this problem was to subtract the "anti-comet" from the "comet" frame and thereby remove the galaxy trails while keeping the image of the moving comet. Unfortunately, this is not the best solution, since it increases the noise in the data by a factor of $\sqrt{2}$.

To overcome this limitation, we are presently working on a new technique. Instead of co-adding the original frames according to a motion opposite to that of the comet, the "anti-comet" frame may be built instead by artificially trailing the "stars" re-combined frame. As this frame has the best S/N-ratio available, the resulting "anti-comet" frame would introduce less noise when it is subtracted, than does the present one.

We mention in passing that as a by-product of the present observational method, a direct combination of the frames allows to count and morphologically classify galaxies to a very faint limiting magnitude. This is of obvious cosmological interest, especially when it is possible to compare the statistics in the diverse directions that correspond to the observed comets.

5.2 New objects

The re-combined frames may also show the images of other moving, very faint objects. For instance, while we re-combined the original images according to the motion of the comet we were pointing to, it is equally possible to re-combine them for any other hypothetical motion. In this way it would be feasible to perform a systematic search for unknown, faint moving objects. Since their direction and rate of motion are a priori unknown, it will be necessary to re-combine the frames for all possible direction and rates of motion, and to look for objects which turn up in one resulting frame, but not in the others. We are now experimenting with this technique.

While a 2σ detection for a known comet is statistically significant (97.7%) because its motion is well known, this signal level would not suffice for a secure detection of a new, otherwise unknown object. For instance, in a 2×2 arcminutes frame (that is the typical size for the SuSI camera), the probability of having a seeing-sized noise-only feature at 4σ over the noise level is no less than 0.37. In other words, any detection at this apparently quite high confidence level has more than a 1/3 chance of being completely spurious ! In fact, to reach a level of significance of 0.99, the S/N-ratio of the object should be at least around 5. However, in most cases, it would probably also be possible to discriminate between a noise feature and a real object by carefully examining the original, individual images in the available frames.

As an example, we mention that the individual frames obtained for P/Halley have been re-combined according to a hypothetical motion of $\Delta\alpha/\Delta t = -6.2''$/h, and $\Delta\delta/\Delta t = +5.2''$/h. (Actually, this velocity was obtained accidentically during the reductions when a wrong pixel size was input into the centering routine !). By direct inspection of the resulting frame an apparently real seeing-size image was found with magnitude V = 25.6, corresponding to S/N = 3.7. Taking into account the statistics of this particular field and the value of the seeing, the significance of this detection is around 0.54, i.e. the probability of finding a noise pattern with these characteristics in that field with that seeing is 0.46. This level of significance is obviously much too low for the object to be considered real, even though it appears to be faintly visible on the individual frames.

6. Conclusions

For the detection of very faint point-sources like very distant comets, the seeing is quite obviously the most critical factor. The finally achievable S/N-ratio varies with the fourth power of the seeing, but only with the square of the mirror diameter and the square root of the exposure time. The active optics of the medium-size NTT and its specially designed dome obviously constitute a substantial advantage for this type of very demanding observational programme. The absence of differential guiding is not critical as long as the exposure time can be kept short.

The preliminary results presented in this paper show that comet Halley is now again in a quiet state. It also provides important experience for the optimization of future observations of very distant comets which may lead to the actual detection or at least put rather stringent constraints on the size of the nuclei of a selection of diverse comets.

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Summary and Discussion of Observations

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There is no doubt that the many new observations of distant comets which have been presented today is a most impressive demonstration of the current progress in an important field of contemporary astronomy. However, rather than just attempting to summarize what has already been said, I should like to emphasize some of the main results and also to add some personal remarks about how I see the present situation from my position on the observational side. This Workshop has brought together for the first time the observers, the experimenters and the theoreticians in this specialized field. Before we leave each other, it is our expectation that we will be able to agree on *what should be done next*. But this very much depends on *what is observationally possible*, and I shall therefore spend most of my time discussing this question.

Thinking back some 20 years, it is obvious that we have witnessed a quantum jump in our observational capabilities. Pat Roemer, whom I had the privilege of meeting several times when I began observations of comets at ESO in the early 1970's, is unfortunately not here today, but I can imagine how happy she would have been to hear about the enormous progress that has happened since she quit observing distant comets. Her work was extremely painstaking, involving long exposures of photographic plates and careful stepping of the plateholder in the predicted direction in order to follow the motion of the comets. By great efforts she was able to push the observational limit to about magnitude 20, but she had few followers; in the end she was virtually alone in the field. It would of course in principle have been possible to observe even fainter and more distant comets with larger telescopes than the ones she used, for instance with the Palomar 5 metre, but I am not aware that such observations were ever made in those days with that telescope.

The recent work by Karen Meech, as reported this morning, shows that we can now reach much fainter, moving objects than before. The limiting magnitude obtained by Olivier Hainaut with the ESO New Technology Telescope, is in some cases beyond 27. This corresponds to a real gain in observational sensitivity of almost a factor of 1000 after just two decades. It is of course the use of larger telescopes with better optical systems and, in particular, the advent of very efficient, digital detectors like CCDs, which have provided the technological basis for this revolution.

This development has now given us the welcome possibility of being able to tackle efficiently *the physics of distant comets*. Indeed, I believe that I am correct in saying that the present Workshop is very much the outcome of the recent discoveries in the outer parts of the solar system, which have been made with the new instrumentation. An obvious example is the identification of a new class of minor bodies beyond Saturn, the Centaurs, of which (2060) Chiron and

(5145) Pholus are the first members; I am convinced that others will soon be found. The latter object was discovered early this year and another even more distant object, 1992 QB1, has just been identified by two of the participants in this Workshop, Dave Jewitt and Jane Luu. Equally great has been the impact of the completely unexpected and rather well documented outburst of P/Halley, first observed in February 1991. These and other observations have already led to quite a few interpretational efforts, and although we obviously still do not fully understand the underlying processes, there has been a great amount of theoretical progress.

Observers of very distant and therefore faint comets are faced with a difficult choice of instruments: whereas the largest ground-based telescopes are certainly the most efficient in collecting the sparse photons from faint objects, observing time at these instruments is not easy to obtain. There is a large factor of over-subscription and access to these facilities must be fought for in direct competition with many other types of research programmes; not all scheduling committees consider solar-system research as important as the observation of cosmological objects. Contrarily, it is generally easier to get time at smaller telescopes like the Danish 1.54 metre at the ESO La Silla observatory. With them, more extended runs are possible, but the total integration times are longer and they still do not reach the faintest limiting magnitudes. So the observer of distant comets has to carefully tailor the programme to the available instrument and always has to set clear priorities. A typical decision is whether a particular object shall be observed in great detail or whether it is more desirable to observe more objects during a "monitoring"-type programme. Clearly, both types of approach have their specific advantages. In the end, the most useful observations are those which best support the physical interpretation of the objects.

The observations of minor bodies in the solar system always begin with the *discovery*. Comets are usually found when they are already quite close to the Sun and with a few notable exceptions which were discovered some months before perihelion, long-period comets with highly eccentric orbits have never been seen at large pre-perihelion distances. It would obviously be desirable to extend the patrol-type observations to fainter limits, but for practical reasons the sky coverage, and therefore the overall chances of finding such objects at large pre-perihelion distances, will remain small for some time to come. I note in passing that future space missions to the "freshest" possible comets will be dependent on the improvement of this observational situation, since they will require years, rather than months, of preparation and transit time to reach their targets.

It is my impression that *astrometry* of distant comets is not always done in the most accurate way. This may be due to the fact that it can be rather time-consuming to connect the observed object to the primary astrometric standards via transfers of secondary standards in the small CCD fields. The only existing positional catalogue with sufficient density for CCD work is the HST GCS with 40 million entries, but the astrometric accuracy is not as high as that of the much less dense PPM catalogue. Careful astrometry is needed to allow the determination of accurate orbits as soon as possible after the discovery; this is especially difficult for very, slow-moving distant objects, cf. 1992 QB1. Good positions also improve the chances of learning the past orbital and evolutionary history of an object, and they may be crucial for the detection of non-gravitational effects.

What concerns *photometry* of distant comets, I note that it is nowadays always performed on 2-D CCD frames which therefore also provide the opportunity of studying structures in the surrounding coma. Nevertheless, most programmes are only aimed at the "detection" of whether or not a coma is present, normally by comparison with the stellar point-spread-function in the frame. On the other hand, there may be important physical information in the coma structure: I think here of the detailed work on the P/Halley outburst by Zdenek Sekanina and collaborators which was only possible because of the availability of extremely deep (and very time-consuming !) observations, cf. the review by Hermann Böhnhardt this morning. I would not be surprised if similar very deep studies of other objects, e.g. of (2060) Chiron and P/Schwassmann-Wachmann 1, would contribute to our understanding of the ejection mechanisms. However, I certainly agree that this is a matter of setting the right priorities for the scarce observing time.

Spectrophotometry has reached fainter and fainter objects, cf. the work by Anita Cochran and collaborators on P/S-W 1 and other objects, as well as the limit detection of CN in the Chiron coma by Mike A'Hearn and collaborators. The impressive Fabry-Perot observations reported by Klaus Jockers give us a foretaste of the future observational possibilities which we may expect when the next generation giant telescopes becomes available, but until then, spectral observations of distant comets are seriously limited. Low-dispersion spectra of magnitude 22 objects still take most of one observing night on the 4-metre class telescopes and unless they are made at the time of an outburst, it is doubtful that they will show anything but pure solar reflection. If the aim is just to obtain spectral gradients, this is more efficiently done by means of multi-colour direct CCD imaging. I note here the possible use of *polarimetry* to show the presence of near-nuclear (unresolved) dust comae, but the expected polarisation is small and long integrations are needed for the kind of objects we are dealing with here.

The question of "activity" has been in the foreground during many of the talks today. What concerns P/Halley, I have always been of the opinion that the nucleus has been active, ever since it was recovered 10 years ago at 11.2 AU at Palomar by Dave Jewitt and his collaborators. I was interested in learning from Beatrice Mueller that after fitting of an advanced rotational model there are still indications of this in the observations obtained in 1984 at 8 AU pre-perihelion distance. In fact, I believe that unless we observe comets at extreme distances, we shall probably never be able to see the naked nucleus at all. What this really means in terms of distance is difficult to say and will most certainly vary from comet to comet. The work by Karen Meech has showed that some comets are very slow in returning to the "quiescent" stage.

Let me now mention what I consider to be some of the major observational "problems", at present and in the immediate future.

Probably one of the most severe restrictions is the uneven "*background*". At low galactic latitudes, the sheer number of stars will force observers to predict the positions of their objects and to look for "holes" in advance of the sessions at the telescope, cf. the case of comet Cernis. At high galactic latitudes, there are more galaxies than stars beyond magnitude 23 or so, and they have different forms and profiles, so they are not as easy to clean away as are the stars which all have the same point-spread-functions. Extremely deep observations with the ESO NTT have shown that at least in some fields, the galaxies cover more than 1/3, possibly even half of the sky at magnitude 29 and beyond. Although it is in principle feasible to observe extremely faint comets (e.g. P/Halley at aphelion) with the new 8-metre class telescopes, it will therefore be next to impossible to avoid overlapping images and the resulting photometric accuracy will necessarily suffer from this. To achieve the highest possible resolution and to preserve the deepest limiting magnitude, it is desirable that distant comets are *tracked* during the observations. Even at very large heliocentric distances, the motions are fast enough to spread the image over several pixels, if the integration time is of the order of 10 - 20 minutes, a practical minimum in view of the non-negligible read-out times. Another problem that is seldom mentioned is the question of the *linearity* of the response of CCDs. The extrapolation of intensities from the relatively bright photometric standards to the very faint objects is not a trivial matter and some caution is necessary when comparing magnitudes of the same object, as quoted by different observers. How accurate are the pre- and post-perihelion magnitudes of P/Halley really? This leads me to repeat the plea, expressed earlier today by Hermann Böhnhardt: that the pre-perihelion P/Halley CCD observations ought to be re-reduced ! Considering the very significant advances in the *reduction methods*, in particular that we have now learned to produce much better flat-fields than before, it would certainly be useful to have a renewed look at these frames. No doubt that the coma detection limits would then reach fainter intensities and that the old question about rotational variations as opposed to activity can be looked into in a more critical way. Older observations of other comets may of course also gain from such a programme.

Let me finally mention what I think may be an important conclusion which can be drawn from today's discussions; it is partly thanks to some remarks from Michel Festou. Karen Meech demonstrated how some comets, for instance comet Bowell, retain a relatively large coma which just fades away as the comet moves outwards until nothing more is seen. On the other hand, thanks to the NTT non-detection at a very faint limiting magnitude, Olivier Hainaut put some very strict limits to the sizes of the nuclei of several comets, which were previously thought to have rather large nuclei, because of their high state of activity (bright absolute magnitudes) at smaller heliocentric distances. Are therefore the nuclei of these comets, and perhaps also of other long-period comets, smaller than believed earlier and is perhaps therefore the amount of mass lost during their perihelion passage a much higher fraction of their total mass? How much is left of the nucleus at all?

Future work on distant comets will help us to elucidate these and other questions. This Workshop will help us to identify the critical observations needed for this.