INVITED DISCOURSES

HALLEY'S COMET (Part I): Ground-based Observations

Richard M. West
European Southern Observatory
Karl-Schwarzschild-Str. 2
D-8046 Garching bei München, FRG

ABSTRACT. Since the recovery in October 1982, an extensive, international programme to observe Comet Halley with ground-based instruments has been coordinated by the International Halley Watch (IHW), and a comprehensive archive is now in the final phases of preparation. The observations were carried out at more than 150 observatories and with all available methods. A special effort was made to support the space missions during the comet encounters in early March 1986. Whereas the spacecraft provided detailed in-situ measurements over a short time interval, ground-based observers have so far followed the development of the comet over a period of nearly six years, and a number of spectacular events near the nucleus and in the tail have been documented in great detail. These observations still continue. This article gives an overview of the most important results obtained from the ground and also mentions the prospects for further observations with large telescopes during the next years.

1. Comet Halley and cometary science

Quite a few excellent books have recently been written about Comet Halley and there is no need to describe once more its role in the history of humanity. Still, an account of the impact of this object on astronomy and associated space sciences during the recent apparition can best be appreciated after a brief glance at some of the results obtained at the time of earlier passages. Cometary science has since long been intimately connected to Comet Halley and it received a tremendous impetus through the intensive observational and interpretational efforts during 1985-86.

Comet Halley belongs to a select group of ten known comets with periods near 70 years. However, five of these have only been seen during a single apparition and among the others, one (Westphal 1913 VI) was not seen at its last perihelion passage and may have ceased being active; one (Brorsen-Metcalf 1919 III) was only seen at two apparitions and the last two (Pons-Brooks 1954 IV; Olbers 1956 IV) have only been observed during three apparitions. In fact, Halley is by far the best known, periodic comet and it has been observed over more than two millennia; it also exhibits virtually all the characteristics of an active comet, from nuclear outbursts to rapid changes in the tail.

More or less detailed astronomical observations are now available at 30 apparitions since *240 B.C.* The earliest data come from China and it is not unlikely that improved orbital extrapolations further back in time will eventually uncover even earlier observations in the ancient annals of that country. However, "modern" studies may be said to start with a drawing by Hevelius on 8 September 1682, showing a prominent, curved jet in addition to a tail. Soon after followed the work by Halley (1705), who recognized that the bright comets in *1531, 1607* and *1682* had similar orbital elements and must therefore be the same object.

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The passage in *1759* - first predicted by Halley - was above all characterized by its crucial importance for the confirmation of Newton's theory of gravitation and also the improved accuracy of *astrometric* observations, due to better instruments and measuring methods. With the help of the frantic work by J.-J. Lalande and his assistant Madame N.-R. de la Brière, in November 1758 A.-C. Clairault was able to announce the predicted perihelion time as 13 April 1759, i.e. only one month too late. But the comet was accidentally recovered on 25 December 1758 by an amateur, J.G. Palitzsch near Dresden; this was also the first telescopic recovery. Ch. Messier found it independently on 24 January 1759, and a certain lack of international cooperation is illustrated by the fact that he was forbidden by his superior, J.-N. Delisle, to announce this until three months later. However, in the meantime Messier went on to produce an excellent series of astrometric positions.

Although Encke (1820) had earlier introduced a non-gravitational term into his orbital computations for the short-period comet that now carries his name, none of the Halley predictions for the *1835* apparition took this effect into account. It is during this apparition that the modern, *(astro)physical* study of comets was inaugurated by several series of detailed drawings of the inner coma, which were made in the course of painstaking, visual observations by F.W. Bessel, F.G.W. Struve, J.F.W Herschel and others; reproductions from the original papers may be found in the atlas by Donn et al. (1986). They documented a pronounced asymmetry and also rapid changes in the emitting light cones, almost exactly 150 years before the spacecraft observations of dust jets.

Another step from *qualitative* descriptions towards *quantitative* measurements was achieved at the *1910* apparition. A new generation of powerful telescopes in combination with the photographic emulsion as detector and information storage medium, resulted in a wealth of useful observations. The photographic recovery of the comet by Max Wolf, at 3.5 A.U. from the Sun, was followed up by at least 1600 photographs, more than 3000 astrometric positions and several dozen photographic spectra. The organization of coordinated observations was suggested by E.E. Barnard already in the 1890's and a "Comet Committee of the Astronomical and Astrophysical Society of America" was created. A "Circular Respecting Observation of Halley's Comet" in 1910 established well defined goals and invited cooperation. Several temporary observing stations were set up in order to get continuous coverage, for instance in Hawaii. However, the coordination failed, because manpower and funding were unable to handle the unexpectedly large number of observations and also because some of the most active observatories decided to proceed independently. In the end, the only comprehensive study was that of Bobrovnikoff (1931), lately supplemented by an impressive collection of 1909-11 Halley photographs (Donn et al., 1986).

Improved orbital computations began to appear in print more than 10 years before the next perihelion passage in *1986*, and the first recovery attempts were undertaken already in 1977. However, the first definite image was obtained on 16 October 1982 with the Palomar 5 m telescope, immediately followed by the 3.6 m CFH and 4 m KPNO telescopes and soon after by the Danish 1.5 m telescope at ESO. The advance of astronomical technology over the past centuries is interestingly illustrated by the interval between recovery and perihelion: 1531 (30^d, recovery magnitude 4^m), 1607 (36^d, $2\overset{m}{.}5$), 1682 (31^d,$2\overset{m}{.}5$), 1759 (78^d, 8^m), 1835 (104^d, $?^m$), 1910 (231^d, 16^m) and 1986 (1212^d, $24\overset{m}{.}5$). Monitoring of the nucleus continued until the comet entered the active state by developing a dusty coma late in 1984 and soon thereafter the presence of CN was detected spectroscopically. Table 1 summarizes some of the major events.

TABLE 1: CHRONOLOGY OF MAJOR HALLEY EVENTS 1982 - 91

Date			r(A.U.)	Event
1982	Oct.	16	11.05	Recovery with 5-m Palomar telescope
1983	Jan.	10	10.53	1^m variation: rotation or activity?
1984	Feb.	4	7.96	First spectrum: reflected sunlight
1984	Sep.	25	6.14	6" coma visible
1984	Oct.	22	5.91	Photometry shows coma contribution
1984	Oct.	30	5.84	30" coma in slit spectrum
1985	Feb.	17	4.84	First spectra with CN and [OH] emission
1985	Jul.		3.3	First radio detection of OH
1985	Nov.	12	1.76	First photos with ion tail
1985	Nov.	27	1.54	Minimum distance to Earth at $\Delta = 0.62$ A.U.
1985	Dec.	9	1.36	Two $3° - 4°$ ion tails
1986	Jan.	10	0.87	Major Disconnection Event (D.E.) in tail
1986	Feb.	9	0.59	Perihelion
1986	Feb.	15	0.60	First photo after perihelion
1986	Feb.	late	0.65	Multiple dust tails; antitail
1986	Mar.	6	0.79	Vega-1 flyby at $d = 8890$ km
1986	Mar	8	0.82	Suisei flyby at $d = 151000$ km
1986	Mar.	8-10	0.83	Major D.E.
1986	Mar.	9	0.83	Vega-2 flyby at $d = 8030$ km
1986	Mar.	11	0.86	Sakigake encounter at $d = 6.99 \cdot 10^6$ km
1986	Mar.	14	0.90	Giotto flyby at $d = 596 \pm 2$ km
1986	Mar.	20-22	1.01	Major D.E.
1986	Mar.	25	1.07	ICE closest approach at $d = 28 \cdot 10^6$ km
1986	Apr.	11	1.33	Minimum distance to Earth at $\Delta = 0.42$ A.U.
1986	Apr.	11-12	1.34	Major D.E. in tail
1986	May	6		η-Aquarids meteor stream
1986	May			Major sunward spike
1986	Jun.	14	1.82	Last photo showing ion tail
1986	Jul.	23	2.75	Last visual detection of tail (0.3°)
1987	Feb.	2	4.84	Last spectrum with CN and C_3 emission
1987	Apr.	1	5.38	Last CCD-image showing faint tail (> 4')
1987	Apr.	22	5.57	Possible outburst; m(total) = 13.6
1987	Nov.	26	7.35	Strong condensation (m = 19.6 within 5")
1988	Feb.	23	8.01	m(total) = 17 within 40"
1988	May		8.6	Asym. coma; dust cloud > 50"; m(nucleus) = 23.1
1989	Feb.		10.4	Predicted m(nucleus) ~ 24
1990	Feb.		12.5	Predicted m(nucleus) ~ 25
1991	Feb.		14.3	Predicted m(nucleus) ~ 26

2. Coordination of observations during the present apparition

The current apparition represents a milestone in cometary research, not only because of the spacecraft encounters, but also because of the successful, world-wide coordination of the entire ground-based observational effort. The value of this vast undertaking has been clearly demonstrated and it will undoubtedly serve as a model for any similar, future programmes in other fields.

The coordination only became possible after the establishment of the *International Halley Watch (IHW)* with the following main goals: *to encourage and support any scientifically valid means of studying the comet; to coordinate activities among ground-based disciplines and with flight projects; to further standardization and to produce a complete Halley archive with all properly documented data.* The IHW was conceived under the auspices of NASA in 1979; Lead Centers at JPL in Pasadena and at Dr. Remeis Sternwarte in Bamberg were created in 1980, and a Steering Group was set up. Regional Centres were set up in various countries, among others in Japan, P.R.China, USSR and U.K. In 1982, the IAU recognized IHW as the sole world-wide coordinator of ground-based Halley observations and the same year close contacts were established between IHW and the Interagency Consultative Group (IACG) that coordinated the Halley spacecraft projects.

In order to achieve the stated goals, and to avoid the problems that had derailed earlier attempts at coordination, the IHW organised itself into eight disciplines, specified by the investigation technology: *Astrometry, Infrared spectroscopy and radiometry, Large-scale phenomena (tail studies), Near-nucleus studies, Photometry and polarimetry, Radio studies, Spectroscopy and spectrophotometry* and *Meteor studies.* A unique feature of the IHW is the *Amateur observation network* which was organized directly by the lead centers. 26 astronomers were appointed "Discipline specialists" with responsibility for the coordination within their respective disciplines. Direct contacts were established to observers all over the world, and the organisational success is reflected by the enthusiastic response: in the end, more than 1000 astronomers and several hundred amateurs from more than 50 countries actively participated in the IHW. Large amounts of data have now been collected (Table 2), which together with those from the spacecraft will soon become available in a unified "Halley Archive". It will comprise a total of $\sim$ 22 Gbytes and is expected to appear in 1990 in the form of computer-readable Compact Discs, in printed form (pending funding) and also as a computer-retrievable data base. A "trial" archive with observations of P/Crommelin during its 1983-84 apparition was prepared by Sekanina and Aronsson (1985).

TABLE 2: IHW ANTICIPATED DATA

Net	No. of data	Observing period
Astrometry	7000	1982 Oct. - continues
Near-nucleus	6000	1982 Oct. - continues
Large-scale	7000	1982 Oct. - continues
Photometry and polarimetry	55000	1982 Oct. - continues
Spectroscopy and spectrophotometry	2500	1984 Feb. - 1987 Feb.
Infrared spectroscopy and radiometry	2000	1984 Dec. - 1988 Feb.
Radio studies	2200	1985 Jan. - 1986 Aug.
Meteor studies	13500	1985 Oct. - continues
Amateur observations	13000	1985 - 1988

In astrophysical terms, the goal of the IHW has been to provide the observational data for the fullest possible description of the cometary phenomena and their temporal and spatial variations. This in turn allows conclusions about the constitution of the coma and the processes near the nucleus, as well as the interaction between the dust and gas tails with the interplanetary medium. The primary aim of cometary physics, namely the study of the nucleus itself, its structure, composition and evolutionary history, is only indirectly possible by ground-based observations; the present break-through in this area is of course due to the in-situ observations from spacecraft. However, the encounters were of relatively short duration and all took place at about the same heliocentric distance. The full benefit of the high-resolution spacecraft data can only be achieved when they are compared with the long time-series gathered by ground-based techniques. For the first time, accurate calibrations of these series in terms of production rates of many individual atomic and molecular species have now become possible, greatly improving the prospects of an accurate quantitative understanding of the evolution during the pre- and post-perihelion phases. From the recovery at the record heliocentric distance of 11 A.U., through the perihelion at 0.6 A.U., and out again to 8.6 A.U. in May 1988, and with the prospect of additional data during the coming observing seasons, the present apparition of Comet Halley has brought nothing less than a revolution in cometary science.

3. Ground-based observations 1982 - 1988

The preparations for observing Halley resulted in a number of conferences, the Proceedings of which reflect the various aspects of pre-Halley cometary research (Ponnamperuma, 1981; Véron et al., 1982; Wilkening, 1982; Gombosi, 1983; Carusi and Valsechi, 1985).

Detailed presentations of the initial results from space and ground may be found in the Nature Supplement of 15 May 1986 (Vol. 321, pages 259 - 366) and also in the Proceedings of two major conferences, the 20th ESLAB Symposium on "Exploration of Halley's Comet" held in Heidelberg in October 1986 (Battrick et al., 1986; Grewing et al., 1988) and the Symposium on the "Diversity and Similarity of Comets" held in Brussels in April 1987 (Rolfe and Battrick, 1987). The reader is referred to these volumes for details and only an overview of the major ground-based results, including some observations made from orbiting satellites, rockets and aircraft, will be attempted here. In view of the importance of the space encounters, special emphasis will be given to the interval 5 - 15 March 1986, and for practical reasons, the observations will be presented by IHW discipline.

3.1 ASTROMETRY

Astrometric measurements of Comet Halley with reasonable accuracy are available since 1607 (Kepler, Hariot and Longomontanus). The non-gravitational forces are now known to arise from the jet effect of outgassing from the rotating nucleus, and they are therefore dependent on several parameters, including the activity level, heliocentric distance and rotational state. For the orbital linkage over several apparitions, they constitute an important source of uncertainty - in the case of Halley, a delay of $\sim$ 4 days per orbital period - although semi-empirical modelling (Marsden, 1985) has been reasonably successful. For instance, Brady and Carpenter (1971) linked observations from 1682 (13 positions), 1759 (243), 1835 (1517) and 1910 (3085) and obtained the perihelion time T_o = 1986 Feb. 9.39474 ET. In a critical study, Yeomans (1977) selected the best 885 positions, including 9 from 1607, and followed the orbit back to the year 837; based on those from 1759 - 1911 alone, he predicted T_o = 1986 Feb. 9.6613 ET. Including observations after the recovery and up to April 1985, Landgraf (1986) obtained Feb. 9.45891. In April 1986, after the encounters, the actual value was found to be Feb. 9.45888 ET (Morley, 1986).

In addition to the interest in the orbital motion of Comet Halley *per se*, the data provided by the IHW Astrometry Net were used by the spacecraft centers for navigation. Also for this reason, an additional effort was made to increase the accuracy of the measured positions and hence the predicted, spatial position of the comet at the time of the encounters. For instance, the 1835 visual measurements were re-investigated, using more precise, modern positions of the reference stars and many of the 1909-11 plates were remeasured (Morley, 1984; Röser, 1987), significantly improving the accuracy. Special, astrometric catalogues with higher density and accuracy than the SAO Catalogue were prepared along Halley's path by means of new astrographic plates obtained at various observatories in the USA and USSR. A conference on "Cometary Astrometry" (Yeomans et al., 1984) provided detailed recommendations for observers and measurers.

The result is gratifying: about 7000 positions from at least 143 observatories have until now been communicated to the IHW Astrometry Net. The r.m.s. residual is of the order of 1 arcsec, and more than 85% of the data are within 3 arcseconds. During the critical period from mid-February until the encounters in early March 1986, several southern observers daily provided the spacecraft centers with accurate positions within a few hours of the observations. This ground-based support provided crucial data for the navigation before the Pathfinder data became available from the Vega spacecraft.

A major problem for cometary astrometry has always been the presumed off-set between the center of the diffuse image of the inner coma, as seen on short-exposure photographic plates, and the actual position of the comet's nucleus; this is known as the *light shift* and reflects the asymmetric light distribution near the nucleus, because the dust is preferentially released on the side which is illuminated by the Sun. A comparison of the Vega- and Giotto-sightlines to the nucleus with the computed orbit from ground-based observations, for the first time allowed a direct determination of this bias as $\sim$ 1100 km ($\sim 1.''5$) at the time of the encounters.

3.2 NEAR-NUCLEUS STUDIES

Three circumstances particularly contributed to the success of the near-nucleus observations. First, the advent of CCD's, which are optimally suited for this purpose (sensitivity, dynamic range, field). Secondly, the IHW Near-Nucleus Net specified and procured a standard set of optical filters, centered on the spectral bands of the most prominent molecules and radicals in the coma (CN, C_3, CO^+, C_2 and H_2O^+) and also at three continuum wavelengths for comparison and dust studies. And thirdly, greatly improved image processing techniques now make it possible to isolate and quantitatively measure even very faint, transient features like gas and dust jets.

A major result: there are discrete sources of activity, on the sunlit side only. In a series of papers before the 1986 observations, Sekanina and Larson (1986) described how they digitized and processed many of the 1910 photographs. With a radial/rotational shift-difference algorithm, they demonstrated an amazing amount of morphological detail in the coma, including spiral *dust jets*, that "unwind" from the nucleus and evolve into expanding envelopes on a time scale of days. The jets are generated by ejection from discrete sources, enabling the authors to determine the nucleus spin vector, a provisional rotation period of $\sim$ 2.2 days, and also to draw a rough topological map of 13 dust vents. The general picture was confirmed by the spacecraft images. Post-perihelion, short photographic exposures in red light showed major day-to-day changes in nuclear activity (West et al., 1986), in support of a non-uniform distribution of vents on the surface.

Similar processing of CCD frames obtained before and after the perihelion passage in 1986 also showed nuclear dust jets. In addition, pinwheel-shaped *gas jets* were discovered in the CN-images (A'Hearn et al., 1986; Hoban et al., 1988) by using a radial renormalization technique. Gas jets were also seen in CCD-exposures behind an [O I] filter, identical with the one in the Giotto Halley Multicolour Camera, but due to the strong dust background near 700 nm, they could not be seen in the [H_2O^+]-filter (Cosmovici et al. 1988). The gas jets do not coincide spacially with the dust jets, and it has been suggested that the organic CHON particles may be the source of the gas by photosputtering.

Another phenomenon, expanding *coma shells*, which was first seen on 1910 photographs by Larson and Sekanina (1985), was studied in detail by Schlosser et al. (1986) on photographs taken in the light of CN. At least 15 spherical shells were observed from Feb. 17 to Apr. 17 and the expansion rate appeared to decrease with heliocentric distance. From the extrapolated ejection-times, a periodicity of 53.4 ± 0.9 hours was found. However, a rediscussion of this material by Celnik and Schmidt-Kaler (1987) casts some doubt on the correct identification of the shells from night to night. A comparison with the onset times of nuclear activity, observed photometrically by Schleicher et al. (1986), indicates that brightening in CN is observed at the time of the release of a new CN shell. Moreover, backwards extrapolation of the outward motion of condensations in the tail, as seen in the light of CO^+, shows that within the uncertainty, plasma release may also occur at the same time.

Some reports about possible splitting of the nucleus may have referred to bright ejecta.

3.3 LARGE-SCALE PHENOMENA

The temporal changes in the dust and gas tails of a comet reflect the complex interaction between the material released from the nucleus and the interplanetary medium. For such studies, continuous monitoring is of the greatest importance, and it is therefore most gratifying that a large number of observers with access to wide-angle cameras decided to participate in the IHW. They were rather well distributed by geographical longitude and by latitude from Antarctica to northern Norway, and the Pacific Ocean "gap" was bridged by well-equipped expeditionary observers on several islands.

The large-scale phenomena commenced with the appearance of a short ion tail by mid-November 1985. Several ion-tails became visible in early December and the first, major disconnection event (D.E.) took place around January 10, 1986. After perihelion, Comet Halley displayed a broad, fanshaped dust tail with seven or more subtails and also several ion tails. A predicted antitail was observed in late February. A spectacular D.E. was recorded on March 8 - 10. The tail reached a maximum length of about $75 \cdot 10^6$ km in mid-April, although the visibility was hampered by the bright Milky Way background. The ion tail disappeared by mid-June 1986 and the last CCD-image to show a pronounced tail was obtained in April 1987. The coma has persisted at least until May 1988 and a strong nuclear condensation became visible in late 1987; since March 1988, it has been experiencing 1^m night-to-night variations, proving that we are at last beginning to see the nucleus again.

About 20 D.E.'s have been observed; at least the major one on March 8 - 10 can unambiguously be connected to the passing of a magnetic sector boundary, detected by the magnetometers on Vega-1 at March 7.87 (Niedner and Swingenschuh, 1987). This is the first direct confirmation of the suspected cause of D.E.'s and underlines their importance for the study of the solar wind.

A long series of wide-field photographs was made by W.Liller on the remote Easter Island. At La Silla in Chile, H. Pedersen and his associates obtained wide-field CO^+ CCD images (resolution 30") during no less than 57 consecutive nights after Feb. 17; the combination of more than 600 individual frames into a video-sequence is nearing completion. Also from this site, a group from the Bochum University obtained narrow-band CN, CO^+, H_2O^+, N_2^+ and CO_2^+ photos over the same period (cf. Celnik and Schmidt-Kaler, 1987). On these, the authors also measured the motion of a large number of tail knots, humps, kinks, etc. and found that the outward velocity increases quadratically with the distance from the nucleus. More than 500 amateur photos were collected and studied in a similar way in Japan (Saito et al., 1987). Of particular value is the large number of photos obtained at the time of the spacecraft encounters, which allows a detailed study of the development of the features which were observed in-situ.

The impressive fan tail of dust in late February was immediately interpreted by Sekanina (1986) as a series of discrete synchrones from isolated dust outbursts near the time of perihelion; the average time interval was $\sim$ 52.5 hours. A sunward spike of dust was observed from April 28 to June 7 up to a distance of 700,000 km and could be explained as due to the ejection of very small particles (Sekanina et al., 1987).

Another large-scale phenomenon, the Ly-α halo, was observed several times from sounding rockets (Opal et al., 1987) and a 2.2 day "breathing" period was found from the data returned by the Suisei UV-imager.

3.4 PHOTOMETRY AND POLARIMETRY

Photoelectric photometry was made in many places through sets of 8 standard IHW interference filters, centered on the major emission lines and the adjacent continuum. These sets were procured and distributed by the IHW Photometry Net; a general calibration allows direct transformation of the measured fluxes to column densities and then to production rates by a suitable model. Observations through diaphragms of different sizes show the radial distribution of the emitting species. As a main result, the photometrically measured H_2O production (from H_2O^+) agreed well with that found in-situ and Halley's production levels could be compared with those of other bright comets from recent years, notably Bennett (1970 II), Kohoutek (1973 XII) and West (1976 VI). Moreover, the deduced rates for OH and CN were compared with radio measurements of OH and HCN.

Among others, long series of observations were made at Mauna Kea (Piscitelli et al., 1986) and by Sterken and collaborators (1987) in New Zealand and Chile. Of particular interest is the 7.4-day periodic variation in the C_2, OH and CN-fluxes which was first described by Millis and Schleicher (1986), and which was also found in the HCN radio data (Schloerb et al., 1987).

The overall brightness of the comet was estimated by many amateur visual observers and a uniform series of measurements was made with the IUE Fine Error Sensor (FES). In general, the photometric behaviour was similar to what was observed in 1910-11, including the typical asymmetry, reflecting the larger, more persistent post-perihelion activity (Green and Morris, 1987).

Linear polarisation data are available from a number of observers from late 1985 to mid-1986, showing a maximum value near 25% and the reversal at a scattering angle near 160°. Post-perihelion circular polarisation was measured by observers at Taricha (Bolivia) and La Silla (Chile). From a comparison with the in-situ dust particle fluxes measured by the impact sensors on the Vega and Giotto spacecraft, Lamy et al. (1987) conclude that the polarimetry is compatible with rough, moderately absorbing silicate grains having a density decreasing with radius, and also with rough graphite grains, or a mixture of the two.

3.5 SPECTROSCOPY AND SPECTROPHOTOMETRY

This IHW net went into action already in early 1984, when a rather noisy spectrum was obtained of the 23^m object (Belton et al., 1987). The spectrum showed only reflected sunlight until the first weak CN emission lines appeared in Feb. 1985 at r = 4.8 A.U. (Wyckoff et al., 1985). From then on, several dozen observers collected the richest spectral material ever obtained for a single comet. This includes a long series of UV-spectra from IUE (e.g. Feldman et al.,1987) and ASTRON (Boyarchuk, et al., 1987), supplemented by spectra from several rocket flights (Opal, 1987).

As Halley brightened, it became possible to gradually increase the spectral resolution, culminating in R=100000 spectra during March/April 1986 (Arpigny et al., 1987) that allowed a complete separation of the [O I] and NH_2 blend at 630 nm and the resolution of the isotopic lines of $^{12}C_2$ and $^{13}C^{12}C$ in the C_2 (0,0) band at 515 nm. Similar spectra of the CN(0,0) R-branch by Wyckoff et al. (1988) have lead to a determination of the $^{12}C/^{13}C$ isotope abaundance ratio of 65 ± 9 while the solar system value is 89. A very large number of spectra was obtained with a variety of telescopes and equipment by Wyckoff and associates (1986). They were able to isolate pure ionic spectra with improved image processing techniques and possibly detected CO_2^+.

A number of observers used the well-established objective prism technique. In addition to slot and long-slit spectra, 2-dimension spectra (aperture plate) were obtained, for instance by Jockers et al. (1987), allowing an investigation of the simultaneous spatial distribution of several ions in the coma, not possible with other techniques.

The spectral data provided a detailed view of the time variations of the various atomic and molecular species in the coma. The spectra which were obtained near the spacecraft encounters could be directly compared to the in-situ data on the radial distribution of the major gaseous components in the coma and good agreement was found in most cases. Similarly, comparisons with CCD-images and photometry done through the IHW filters were useful to ensure the overall data compatibility.

3.6 INFRARED SPECTROSCOPY AND RADIOMETRY

Several very successful programmes were carried out in the infrared region. Ground-based observations in the near-infrared bands from high-altitude sites were complemented with important data, also at longer wavelengths, which were gathered during several flights of the Kuiper Airborne Observatory (KAO).

Comet Halley was regularly monitored from Sept. 1985 until June 1986, mostly in the standard JHKLMNQ infrared photometric bands (1.2 - 20 μm), and through diaphragms of varying sizes. These measurements allow an analysis of the temperature, production rate, particle size and composition of the dust in the coma. Large variations in the amount of dust were observed, reflecting jet activity also seen in the visual region, but there was no evidence of changes in the nature of the dust over this period. The infrared polarisation was measured in the J, H and K bands and pointed to a two-component dust population (Brooke et al., 1987).

Within infrared spectrophotometry, a major event was the first, unambiguous detection of H_2O emission in a comet at 2.65 μm; the line was seen in high-resolution spectra from a Fourier Transform Spectrometer (FTS) onboard KAO. This difficult observation was only possible when the line was Doppler-shifted sufficiently into the wings of the strong terrestrial absorption line, in December 1985 and March 1986. Expansion velocities of about 1 km/sec were measured (Larson et al., 1987). The measured H_2O production rate was about 10^{30} mol/sec in March 1986, confirming water as the dominant species. Other results from the KAO include a measurement of the ortho-to-para H_2O-ratio; a value of 2.2 - 2.3 was found, indicating a nuclear spin temperature $\sim$ 25 K. OH rotational emission was detected at 119 μm. A search for methane emission was negative and yielded an upper limit for the production rate at about $4 \cdot 10^{28}$ mol/sec. The silicate feature at 10 μm was easily detected, and a new emission feature at 28 μm may be attributed to dust emission.

In the 3 - 4 μm band, emission was detected from formaldehyde (H_2CO) at 3.6 μm; other lines were from CO_2, CO and possibly OCS. Two unidentified emission features at 3.28 and 3.37 μm are thought to originate in the C-H bond in unsaturated and saturated hydrocarbon molecules, respectively, and are also present in the spectra of interstellar dust clouds. It is not known whether the emitter is gaseous or solid; in the first case, the relative, global abundance of carbon in the coma would be no less than 50% of the water abundance. However, the emission could also be thermal, from small dust grains (Encrenaz, 1988).

3.7 RADIO STUDIES

The radio studies of Comet Halley commenced as early as January 1985 when the Nancy radio telescope began to monitor the 1665 and 1667 MHz OH lines in a programme that lasted until the end of August 1986 (Gérard et al., 1987). The first detection was made in early July 1985, almost simultaneously with this telescope and also with the NRAO 43 m antenna. The OH production and kinematics were studied; a peak rate of $3 \cdot 10^{29}$ mol/sec was reached in January 1986 and ΔV increased from 2 km/sec in November 1985 to 3 km/sec in March 1986. A possible 7.1 day variation in the January 1986 data was not seen in those from March and April.

More than 30 radio observatories participated in the Halley observations. Of particular interest is the long series of measurements of the HCN rotational emission at 3.4 mm which was made with the 13.7 m antenna at the Five College Radio Astronomy Observatory (Schloerb et al., 1987). The variations followed the 7.4 day period of the C_2-flux, discovered by Millis and Schleicher (1986).

Several groups attempted to detect more complex molecules. However, the radio searches for HNC, HC_3N, CH_3CN, HCO^+, OCS and CO were negative. Radar contact was established with the Arecibo 300 m antenna in late November 1985, but it is doubtful that any scintillation enhancement from Halley's plasma tail was seen during occultation observations of compact radio sources in early 1986 (Ananthakrishnan et al., 1986).

Many of these results are extensively discussed in the Proceedings of a follow-up meeting on "Cometary Radio Astronomy" (Irvine et al., 1987).

3.8 METEOR STUDIES

Comet Halley is the parent body of two meteor streams, the Orionids with peak activity near October 21, and the η Aquarids around May 3-5. Visual and radar observations were therefore stepped up in October 1985 and May 1986, respectively, although fresh injections of dust particles could not yet be expected to be observed on these dates (Babadzhanov et al., 1987). Indeed, even less meteors were observed than in previous years (Hajdukova et al., 1987), but these observations serve as a useful comparison for the coming seasons. Spectra of some Orionid meteors show them to be essentially similar to meteors from other showers; the brightest are produced by meteoroids with masses of several grams.

3.9 AMATEUR CONTRIBUTIONS

Astronomy is one of the few sciences where the amateur still plays an important role and cometary astronomy is a classic amateur domain. In recognition of this potential, the IHW created an Amateur Net and a comprehensive Manual was issued (Edberg, 1983); it was also translated into several other languages, including Japanese.

The coordination bore fruit in several ways. First, it resulted in about 10000 magnitude estimates, 700 drawings of the visual appearance, about 2000 photographs, many of high quality and very useful for the large-scale investigations, and about 50 spectra. Secondly, and equally important, the Halley programme taught many amateurs how to make scientifically useful observations and left them well prepared for future work. The feeling of being involved in "real science" was of great satisfaction to many amateur participants and a good advertisement for astronomy in contemporary society.

4. Conclusions and outlook

Never before have so many astronomers been mobilized for the observations of a single object and never before has such a rich material been obtained with so many different methods. The organization of the observations of Comet Halley by the IHW has been an unequalled success and long after the initial studies are over, important research will continue on the basis of the enormous archive. The intensive collaboration between space- and ground-based observers has blazed the trail for future projects, also outside the present field.

But the ground-based Halley campaign is not yet over and some of the IHW Nets will continue to produce new observations for some time. Long CCD exposures still permit a morphological study of the coma and therefore of the diminishing activity. They also provide information about the varying brightness of the nucleus. Astrometric positions can be determined as long as the nucleus can be detected and may eventually throw more light on the troublesome non-gravitational forces.

After so many new discoveries, it is almost ironic that the major outstanding problem is the rotational state of the nucleus. It was impossible to determine unambiguously the rotation period from distant, pre-perihelion photometry alone, but the study of jets (1910) and outbursts (1986) seems to favour a period near 52 hours. This period would also appear compatible with the Vega and Giotto views of the nucleus. However, a 7.4 day periodicity was found in coma photometry and radio measurements soon after perihelion and since then several authors have tried to reconcile the data by introduction of the effects of nutation and precession; a comprehensive summary is given by Sekanina (1987) and the formal theory is described by Kamél (1988).

It is not obvious that the rotation of the nucleus will be clearly reflected by major changes in the coma and it may therefore be futile to attempt a linkage between the early pre-perihelion data and measurements of the well-developed coma in 1985-86. However, the knowledge of the rotational state and therefore of the attitude during the spacecraft encounters is of course of crucial importance for the determination of the three-dimensional shape of the nucleus and the surface topology. Some observers with access to large telescopes have therefore decided to continue photometric measurements of the "bare" nucleus at large heliocentric distances. The attempts in 1987 were unsuccessful because of a persistent, opaque coma and only from March 1988 can the nucleus again be seen and measured during excellent seeing, as a central light spike in the inner coma.

As part of this renewed effort, observations have been performed with the Danish 1.5 m telescope at the ESO La Silla Observatory. A composite image of Comet Halley was prepared from more than 50 individual CCD frames, obtained during 19 nights in April - May 1988 and totalling 11^h15^m exposure time (West and Jørgensen, 1988). At this time the heliocentric distance was 8.6 A.U.. The 23^m cometary nucleus is seen in an asymmetric "inner" coma, surrounded by a much larger, "outer" coma, more than 50", or 300,000 km across, cf. Fig.1. The brightness of the nucleus varies by more than 1^m; it was not yet possible to determine the period unambigously. Subtracting the composite image from its own rotationally symmetric mean, an fan-shaped area of enhanced surface brightness at the 27.5^m per square arcsecond level is seen in the SE quadrant, i.e. opposite the direction

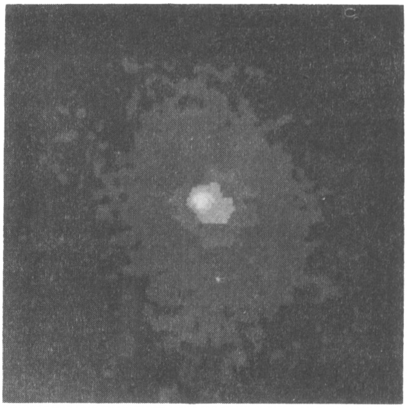

Figure 1: Comet Halley in April-May 1988; see text

to the Sun. These findings indicate that some dust is still being released into the coma and from there it is lost into interplanetary space via a dust tail, albeit exceedingly faint.

Hopefully more measurements of this type will follow in 1989 and, by use of the largest ground-based telescopes, also in 1990 and possibly in 1991 as well. After that the HST may take over. Not only may such observations provide a firmer basis for the determination of the rotation of the nucleus; they also carry cometary research further into the outer reaches of the solar system than ever before attempted.

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