20. POSITIONS AND MOTIONS OF MINOR PLANETS, COMETS AND SATELLITES
POSITIONS ET MOUVEMENTS DES PETITES PLANETES, DES COMETES ET DES SATELLITES

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I INTRODUCTION

In the past triennium members of the Commission 20 have been very active in studying positions and motions of minor planets, comets and satellites including rings by observational and theoretical investigations, as it is described in this report. In fact observers have been producing tremendous amount of astrometric data, much more than we could imagine twenty years ago, when we heard many complains and appeals to observers for needs of more observations, particularly, for minor planets and satellites. Technically, several new devices to detect faint objects and to measure their positions more effectively, have been developed. Theoreticians have faced many interesting and important problems to explain observational facts with several powerful methods developed recently.

For minor planets as observers produced over 20 000 observations each year, 300 orbits were determined by combining them with those of unnumbered minor planets and the number of the numbered minor planets is more than 3700(October 1987) as 200 minor planets were given their permanent designations annually. Although three lost minor planets were recovered at the end of 1986, three are still lost. Theoretically, many papers tried to explain the causes of Kirkwood gaps and behaviors of so-called secular commensurability regions, among others, as they are still very important problems to study dynamical stabilities and the distributions of minor bodies in the solar system.

For comets P/Halley, particularly, had attracted great attentions, as 6000 astrometric positions were obtained by 140 observatories. In the period of July 1984-June 1987 14 short-period and 18 long-period comets were discovered and 32 previously known comets were recovered. Since several papers on relations of possible periodic impact events and biological extinctions were published, many authors restudied dynamical evolutions of cometary orbits, particularly, by investigating perturbations by known stars and molecular clouds and by tidal forces of the Galaxy in the Oort clouds.

As Voyager spacecrafts discovered several faint satellites and ringlets, with very peculiar characteristics, of Saturn and Uranus, important contributions were made to explain their distributions and dynamical structures. Even for bright satellites several new theories of motion were published by using many new observations. There are still several important problems to be solved, particularly, their orbital evolutions to the present configurations of satellite systems.

Since the importance of occultations of minor planets, satellites and rings has been increased, the Commission 20 reorganized the Working Group on Occultations to try to coordinate observational activities and to channel useful informations to observers quickly. There have been several successes including determinations of the size and the shape of the minor planet, (1) Ceres.

As the activities of the Commission were increased, the number of its members was increased beyond 150 during the previous General Assembly at New Delhi. However, it is a sad news to have heard that Prof. Zhang Yu-Zhe, one of the oldest members of the Commission 20 and formerly the director of the Purple Mountain Observatory, was deceased on July 21, 1986 at the age of 83.

This report consists, besides the Introduction, of 4 Sections, namely, on Minor Planets, Comets, Satellites and Occultations, which were drafted, respectively, by B G Marsden, the director of the Minor Planet Center, and E Roemer, J-E Arlot and R L Millis, who are chairmen of Working Groups on the respective subjects, and was compiled and edited by Y Kozai, who also wrote the Introduction.

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II MINOR PLANETS

a) General

Astrometric and orbital work on minor planets has been maintained at very high level of activity during the 1984–1987 triennium. The two publications sponsored by the Commission 20, the *Minor Planet Circulars*(MPC) and the *Efemeridy Malkh Planet*(EMP), continue to be the most visible indicators of this activity. The monthly batches of MPCs are issued by the Minor Planet Center at the Smithsonian Astrophysical Observatory under the direction of Marsden with assistance from Bardwell, Green and, since mid-1986, Nakano. The annual EMP volumes are published by the Institute of Theoretical Astronomy(ITA), Leningrad, under the direction of Batrakov with assistance from Ashkova, Vinogradova, Izvekov, Sumzina and Shor. Kastel' and Filippova also participate in the ITA work on minor planets.

The now rather stable annual production of about 1000 pages of MPCs has again included between 20 000 and 25 000 astrometric observations of minor planets. Further editions of the complete set of available observations on magnetic tape were issued in 1985 and 1986. The 1986 edition contained 275 636 observations of numbered and 101 179 of unnumbered minor planets; the latter included the 15 283 observations from the Palomar-Leiden survey that were made generally available for the first time in the 1985 edition of the tape and that had never appeared in print. The plan is that future editions of the complete tape will be issued less frequently, because all the observations published in the MPCs subsequent to the preparation of the 1986 tape have been made available on diskettes in MS-DOS format issued in conjunction with the printed batches of MPCs. The MPCs contain annually more than 1000 elliptical orbits computed, when there exist observations on three or more nights at a single opposition. There are also nowadays almost 300 orbits annually where observations of unnumbered minor planets can be linked at different oppositions, as well as almost 200 that refer to minor planets being newly given permanent numbers; improved orbits are also included each year for 100 already-numbered minor planets. The aforementioned MS-DOS diskettes contain, in addition to the observations in each batch of MPCs, all the pages that include orbital data.

In September 1986 the Minor Planet Center published editions of the "Catalogue of Orbits of Unnumbered Minor Planets" and the "Catalogue of Discoveries and Identifications of Minor Planets". With entries for 7095 objects the new orbit catalogue was almost three times larger than the previous 1982 edition, although almost half of the increase was due to the incorporation of all the orbits from the Palomar-Leiden survey. The number of multiple-opposition orbits, 855, was more than four times that in the 1982 edition. The discovery listing in the companion volume contained reference to 40 754 provisional designations (plus 145 P-L objects), compared to 29 157 in the 1982 edition, while the count of identifications with numbered minor planets had increased from 8550 to 12 580. The 7095 orbits were also issued on an MS-DOS diskette, as were the orbits for the 3495 minor planets numbered by that time, the latter having been updated to the standard epoch, July 24.0, 1987, and for the most part prepared by the ITA. By applying a computer program provided with the MPC diskettes users can collect in the same form all the additional orbits (for numbered and unnumbered objects) contained month by month in the diskette edition of the MPC orbit pages. Both the MPC diskettes and the orbit-catalogue diskettes also include computer programs for ephemeris computations.

The "dial-in" computer service, operated around the clock by the Minor Planet Center in association with the Central Bureau for Astronomical Telegrams, has continued to gain in popularity since its introduction in 1984, and it is now also supported by a back-up computer when the principal computer is unavailable. The user can select orbital elements and compute ephemerides, and a useful new feature, introduced in 1986, allows him to verify if particular observations can be identified with numbered minor planets. Observers are also increasingly finding the computer service convenient for submitting their observations to the Minor Planet Center, and the Center has responded by quickly providing observers with identifications or designations for their new discoveries.

The EMP volumes were published for 1986, 1987 and 1988, successive volumes increasing in size as more new minor planets are numbered. The 1988 edition contains 366 pages. The EMP pages are now prepared with the help of a computer program that utilizes a specialized computer typesetting system devised by Glejbman. In addition to the actual production of ephemerides much of the computing work involves the annual updating of the osculating elements to later epochs, and these updated elements are now also available in machine-readable form through the Stellar Data Center, Strasbourg(41.002.068). ITA staff members have computed 385 improved orbits for EMP 1986-1988 and already computed 150

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for EMP 1989. The standard accuracy is now such that the positions of the great majority of the numbered minor planets can be predicted within a few seconds of arc, and less than 0.5 percent of the orbits yield ephemerides that are in error by more than 20 arcsec. ITA also prepares and distributes to participating observatories daily ephemerides for the 20 selected planets used in the ongoing program for examining systematic errors in star catalogues.

Implementation of the resolution by the Commission 20 at the 1985 IAU General Assembly concerning the new two-parameter magnitude system for minor planets was begun in January 1986. The first step consisted of the use of the single slope parameter, G=0.25, and stop-gap values of the visual absolute magnitude, H, derived from the old photographic value, $B(1,0)$, by $H=B(1,0)-1.0$. Tedesco of Jet Propulsion Laboratory made a preliminary analysis of the photometric data in his possession and prepared a new set of parameters (utilizing additional fixed values of G=0.15 and G=0.40 but in 237 cases making actual solutions for G) for minor planets, (1)–(3318). After some minor modifications and systematic extension (again with the single value G=0.25) to the minor planet (3495) by Marsden, these parameters were published in the MPCs in September 1986. The system has subsequently been extended in the same way to new minor planets when they are numbered (although for unnumbered minor planets the values of H are generally rather rough values given only to 0.5 magnitude). The values of H and G given in the EMP for the first time in 1988 are identical with those in the MPCs. It should be noted that, contrary to former practice, the predicted magnitudes for the fourth date in the standard opposition ephemerides in EMP 1988 do now include the phase effect.

b) Observations and Orbits.

Photographic observing programs that include an emphasis on the discovery of new minor planets have continued with wide-field instruments at Brorfelde(Jensen), Caussols(Heudier), Cerro El Roble(Torres), El Leoncito(Sanguin), Flagstaff(Bowell), Kiso(Kosai), Klet(Mrkos), Kvistaberg(Lagerkvist), La Silla(Debehogne, Elst and Ferreri), Nanjing(Zhang), Nauchnyj(Chernykh), Palomar(Helin, Shoemaker and Shoemaker), Perth(Candy), Smolyan(Elst and Shkodrov), Tautenburg(Borngen) and Zimmerwald(Wild), as well as by amateur astronomers, Seki, Urata and others in Japan, and Colombini, Baur and associates in Italy. New programs have been undertaken at Haute Provence(Dossin and Elst), Kavalur(Rajmohan), Pizskesteto and Piwnice(Antal) and Siding Spring(McNaught). Extensive photographic follow-up observations of unnumbered minor planets have been made as in the past, in particular, at Oak Ridge(McCrosky) and Mount John(Gilmore), and numerous photographic observations have been made at Victoria(Tatum and Balam), as well as by amateur astronomers in Japan, Australia(Herald) and the United States (Handley). Bus continued his extensive "UCAS" survey of March-April 1981 by finding and measuring images of some 80-percent of the objects in February and/or May.

Several of aforementioned programs, particularly, those at Flagstaff, Klet, La Silla, Nanjing, Nauchnyj, Perth and Zimmerwald, also yield many observations of numbered minor planets. Several USSR observatories(Abastumani, Dushanbe, Goloseevo, Kazan, Kharkov, Kitab, Moscow, Nauchnyj-Pulkovo Southern Station, Nikolaev, Pulkovo, Saratov, Tartu, Tashkent, Zvenigorod and Zelenchuk-Kazan Southern Station) concentrate on numbered minor planets, particularly, the ITA program of 20 selected objects. Other observatories involved with numbered minor planets are Asiago(Ferreri), Barcelona(Codina), Bordeaux(Rapaport), Cape Town(Churms), Cerro Calan(Wroblewski), Chorzow(Wlodarczyk), Hoher List (Geffert), La Palma(Morrison), Lick(Klemola), Pino Torinese(Zappala), Poznan(Hurnik), Quonochontaug (Penhallow), San Fernando(Quijano), Skalnate Pleso(Svoren) and Yebes(de Pascual), and there is also participation by amateur astronomers in England, France, West Germany and Italy(Balbi, Bonk, Bressler, Buczynski, Chanal, Lai, Manning, Quadri and Seiler). Quijano specifically reports that the ITA objects have been under observation with the Carte du Ciel astrograph at San Fernando, as have the 63 minor planets being observed in connection with the Hipparcos project, a total of 1062 oppositions having been obtained during the triennium from 354 plates.

CCD astrometry on minor planets, a pioneering activity at the time of the last report, has again been pursued during the current triennium in the same three pioneering programs, namely, with the Flagstaff 1.7m reflector(Bowell), the Palomar 1.5m reflector(Gibson) and the Steward Observatory's 0.9m reflector on Kitt Peak(Gehrels and Scotti). The principal problem with CCD astrometry is the expense of large CCD chips, so the available fields are even smaller than when large reflectors are used for photographic astrometry, and field plates are normally necessary for the reduction, a time-consuming process. The chip used in the Steward program, for example, yields a field only 11 arcmin across; this particular program(Spacewatch), however, utilizes the earth's rotation to make long scans in right ascension around the minor planets of interest, and it can be assured that there are enough SAOC reference stars to permit the reductions, which have frequently been completed on the same day when the observations are made. Another source of quick but reliable positions has been the 2.2m reflector at Mauna Kea, where Tholen has simply but effectively made use of the telescope's encoders to derive positions of minor planets relative to SAOC stars.

As in the past three members of the Commission 20, Bowell, Edmondson and Oterma, have continued to cooperate extensively in the measurement and sometimes remeasurement of old plates at their respective observatories(Flagstaff, Indiana and Turku). Most of the requests for measurement are channeled through the Minor Planet Center and are in response to identifications that have been suggested. West has used the facilities of the European Southern Observatory to remeasure some of the old Heidelberg plates, notably those of (473) Nolli, (719) Albert, (1026) Ingrid and (1179) Mally, lost minor planets observed only at their discovery oppositions. Following the remeasurements for (1179), Schmadel redetermined the orbit allowing the object to be found (the first recovery of a lost numbered minor planet since 1982) on a pair of plates taken by Schuster at its favorable opposition in 1986; the identity was confirmed by West's subsequent discovery and measurement of images on the Palomar Sky Survey and on exposures with the ESO and UK Schmidts. Inspired by this news in December 1986, but without the new Heidelberg measurements, Nakano was able a few days later to identify (1026) with an object observed on two nights earlier in 1986 and with single observations in 1981 and 1957. West's new remeasurements of 1901 plates of (473) had a pronounced effect on the orbit determination, and on receiving them on New Year's Eve, Marsden was quickly able to find identifications for this object in 1940, 1981 and 1986; although there was not a recognizable similarity of elements, a rather poor elliptical orbit had in fact actually been published for the identity 1981 QR. The Heidelberg discovery, (719) as well as (724) Hapag and (878) Mildred, remain lost. Gibson has remeasured the original Mt. Wilson plates of (878), but this object is evidently too faint to be identified in the existing database of observations of unnumbered minor planets. (724), one of the many visual discoveries by Palisa, remains the only numbered minor planet not known ever to have been photographed.

Multiple-opposition orbit computations have been performed by staff members of both the Minor Planet Center and ITA, by Dirkis(Riga), Hurukawa(Tokyo), Kristensen(Aarhus), Landgraf(Goettingen), Schmadel (Heidelberg) and Yeomans(Pasadena), and also by amateur astronomers in Japan(Kobayashi, Oishi and Urata), Belgium(Goffin) and Canada(Lowe). Most of the orbit computers have also been extensively involved with establishing identifications, as also have Bowell(Flagstaff) and further amateurs in Japan (Furuta), West Germany(Kippes) and the United States(Bowman). Utilizing his capability of working with survey plates taken with the large Schmidt telescopes, West has been able to confirm or deny some of more questionable identifications. Bus has also made use of Palomar Schmidt plates taken by Kowal during 1977–1979 to find images of several hundred UCAS objects at earlier oppositions.

Interest in establishing identifications continues to grow, and Marsden(41.098.017) reviewed the various methods that are used, which nowadays generally range from automatic comparison of observations of a minor planet on two nights with all the available orbits, through the more straightforward consideration of the similarity of two preliminary orbits, to the comparison of variation orbits of a particular object with all the available observations. Some researchers, notably Oishi, have recently sucessfully used as input for the last method starting orbits derived from potential multiple designations of the same object at the basic opposition. Intriguing new possibilities involves cases where there exist observations on no more than two nights at any of the oppositions concerned. In response to a condemnation by Taff(38.042.035) of the Gauss method of orbit determination from three observations, Marsden(40.042.003) demonstrated that Gauss linkages of two observations at one opposition with a series of candidate third observations at a neighboring opposition is (when there is a confirming observation on a second night at the neighboring opposition) an effective way of achieving this. Lowe and Nakano have also subsequently found some identifications of this general type from the similarity of likely two-observation "Vaisala" orbits at different oppositions or by adopting a series of Vaisala computations for the variation orbits. A paper by Laucenieks and Dirikis(*Novejshie Dostizhaniya v Teorii Komet i Dinamike Malykh Tel*, Moscow, 1986) tried to determine the maximum-likelihood region on the celestial sphere at a given moment for an object with an uncertain preliminary orbit.

van Houten reports that results are now almost complete from a new Trojan survey utilizing 85 plates taken in 1977 by Gehrels with the 1.2m Schmidt telescope at Palomar. The plates were blinked at the Leiden Observatory by van Houten-Groeneveld, who also measured the rectangular coordinates at

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the Catholic University in Nijmegen. Magnitudes were measured by Wisse-Schouten with an iris photometer at Leiden. Orbit computations were made by Bardwell of the Minor Planet Center. Orbital elements have been obtained for 1478 minor planets, of which 26 are new Trojans, four are Hungarias and one is a Hilda. Among the minor planets observed there were also 25 numbered objects and 17 that had previously received provisional designations. A similar survey, utilizing 78 plates taken in 1973, is in progress. Plates blinked by van Houten and van Houten-Groeneveld have been measured by the latter. Their photometry and orbit computations are expected to start soon.

Johnston, Wade, Seidelmann, Kaplan and Carroll have continued their observations of (1) Ceres, (2) Pallas, (4) Vesta and (10) Hygiea with the Very Large Array in Socorro, New Mexico. With other collaborators they made an analysis of the microwave spectrum of (1) Ceres. Of recent discoveries of minor planets 1985PA, 1986JK, PA, WA and 1987MB are Apollos, 1984QA, 1986EB and TO are Atens, and 1985JA, TB and WA, 1986DA, LA, NA and RA are Amors. 1986TO and 1987MB could be identified with 1983UH and 1959LM, respectively.

c) Theoretical Investigations

Bien and Schubart studied the long-period evolution of real and fictitious Trojan orbits by means of Labrouste's method(39.098.032), concentrating, in particular, on orbits close to secular resonances(39.098.030 and 41.098.046); they completed these studies by deriving three characteristic orbital parameters for the numbered Trojans(41.098.045 and *Astron. & Astrophys.*, **175**, 292 and 299). Erdi(39.098.031) showed that, depending on the amplitude of the libration about L4, there is a critical inclination, above which the line of nodes advances. Barber(41.098.047) suggested that long-term perturbations by Saturn might explain the observed difference in the numbers of observed Trojans around L4 and L5. Continuing his analytical work on the Trojans, Garfinkel(40.042.009) investigated the kinematics of the family of homoclinic orbits that is doubly asymptotic to short-period orbits about L3. Zagretdinov(41.098.071, *Kinem. Fiz. Nebešn. Tel*, **2**, 68 and 77) generalized some of Garfinkel's earlier results to the case of inclined orbits, and obtained an intermediate orbit in the circular restricted three-body probelm that could be used to determine the libration motions of 38 known Trojans(42.098.005). Agafonova and Drobyshevskij(40.098.010) discussed the origin of the Trojans in terms of explosions in icy envelopes of Jupiter's Galilean satellites and the eventual transfer of collisonal fragments of the Trojans into typical short-period comet orbits.

Following Wisdom's pioneering work, Murray and Fox(38.098.013) confirmed the qualitative behavior of chaotic trajectories that arise at the 3:1 commensurability with Jupiter. Wisdom(40.042.057) identified the principal cause of large chaotic zone. Sherbaum and Kazantsev(40.098.007) demonstrated that the eccentricity of an orbit in 3:1 resonance increases to the point of making encounters with Jupiter possible. Sidlichovsky and Melendo(41.098.009) extended the Wisdom method to 5:2 resonance and presented computations that strongly support the collisional hypothesis for gap formation. Continuing their work on the depletion of the outer part of the minor planet belt, Milani and Nobili(39.098.021 and 39.098.029) established the dominant importance of libration and secular resonance effects for stability there, and with Murray they(41.098.044) showed that there are differences in the topology of the level manifolds near the 3:2 and 2:1 resonances, an extensive chaotic region being identified in the former case and to a lesser extent in the latter(42.098.052). Ferraz-Mello(*Astron. J.*, **94**, 208) analytically modeled the planar motion of high-eccentricity objects near first-order resonances and deduced approximate laws relating semimajor axis and eccentricity at the libration center and giving proper period of small-amplitude librations around the libration center and the amplitude of the forced oscillation induced by Jupiter's orbital eccentricity; these laws were found to be closely followed by the observed Hilda planets.

In a series of papers on orbital resonances Liu, Innanen and Zhang(39.042.062, 39.042.063 and 40.098.006) established the principal perturbative effects on the orbits of minor planets in resonance with Jupiter. Sergysels and Wettendorff(38.098.086) discussed the gaps in the main belt from the implication from Moser's work that circular orbits at resonances of order up to 4 evolve toward resonances, but they were unable to explain the Hilda group. Henrard and Lemaitre(39.098.028 and 39.028.034) discussed the gaps at 2:1, 3:1 and 5:2 resonances by means of the adiabatic effects of the slow dissipation of the solar nebula at the origin of the solar system. Analysis by Gerasimov(41.098.101, 42.042.085, 42.098.006 and *Astron. Zh.*, **63**, 768 and 1215) of orbits near resonances of the first, second and third orders led to the development of analytical expressions for the orbital elements in terms of Weierstrass functions. Babadzhanov, Zausaev and Obrubov(40.098.012) discussed the influence of resonances on the progressive evolution of Apollo, Amor and Aten objects.

Kozai(40.098.008, 42.042.102 and 42.098.078) calculated mean values of the reciprocal of the distances of the minor planets from Jupiter and hence the secular perturbations on the assumption of circular and planar motions of disturbing planets and that the critical arguments are fixed at stable equilibrium points, and concluded that, unlike short-period comets, most minor planets can avoid close approaches to Jupiter by various kinds of mechanisms. Nakai and Kinoshita(40.098.081) examined the secular perturbations at secular resonances by a semi-analytical method with the use of numerical averaging for both non-resonant and resonant objects. Scholl and Froeschle(41.098.042, 42.042.025 and 42.042.049) extended numerical integrations for up to 1 000 000 years at the three secular resonances near the inner part of the main belt, and concluded that strong eccentricity variations can produce direct earth crossers.

Lidov and Vashkov'yak(39.098.088, 41.098.072, 41.098.090, *Kosm. Issled.*, **24**, 513 and *Astron. Geodez.*, **14**, 22) continued work on secular perturbations, and described a numerical-analytical method for investigating the averaged restricted circular n-body problem and calculated the extreme characteristics of the evolving orbits. Simovljevic(38.098.023) developed an approximate method for determining the mutual perturbations during close encounters between minor planets. Lazovic and Kuzmanoski(41.098.106) have examined occasions when the first four minor planets pass within 0.001AU of other numbered minor planets and found 13 cases of significant perturbations. An orbit improvement by Schmadel(42.098.057) of (29) Amphitrite over 1825–1985 yielded a value of 1047.369±0.029 for the mass ratio of the sun to Jupiter. Scholl, Schmadel and Roser(42.098.059) attempted to determine the mass of (10) Hygiea from its perturbations on (829) Academia.

With an application to the case of (126) Velleda, Arazov and Gabibov(38.098.112) showed that theories of the motions of non-resonant main-belt minor planets can be made using for an intermediate orbit the internal variant of the generalized problem of three fixed centers. Batrakov(39.098.105) developed a maximum-likelihood method for determining the orbit of a minor planet over several oppositions from orbital parameters derived at each opposition separately. Shefer(*Analiz Dvizheniya Nebesn. Tel Soln. Sistemy i Ikh Nabl*, Riga, 1986 and *Astron. Geodez.* **13**, 59 and **14**, 77) showed that the use of regularized equations of motion and variations can be highly efficient for orbit improvement. Shor(*Byull. Inst. Teor. Astron.*, **15**, 593) described the technique used at ITA for refining predictions for occultations by minor planets when last-minute observations are available. Hahn and Rickman and also Benest and Bien(39.098.047, 40.098.028 and 41.098.048) carried out long-term integrations on several minor planets observed between 1979 and 1984 to have cometary orbits. They demonstrated, in particular, that 1983 SA and 1983 XF exhibit temporary librations about the 4:3 and 2:1 resonances with Jupiter.

Zappala, Farinella, Knezevic and Paolicchi(38.098.014) found that, although the general features of the mass distributions of members of Hirayama families can be interpreted in terms of collisional disruption of a parent body and the self-gravitational reaccumulation of the largest remnant, there remain difficulties in the way, by which families are defined(41.098.038), and the abundance of large objects with high angular momenta indicates that the original population of minor planets was several times greater than it is now(41.098.039). Differences between proper elements calculated by the Yuasa theory and the Brouwer and Williams values were discussed with regard to accuracy, particularly, for objects of high eccentricity and/or inclination(41.098.041); in collaboration also with Carpino, Gonczi and Froeschle, the accuracy was also investigated by simulating numerically the dynamical evolution of the families assumed to arise from the explosion of their parent objects(42.098.029). Davis, Chapman, Weidenschilling and Greenberg(39.098.051) simulated a collisional evolution of hypothetical initial populations of minor planets that would yield the observed number of major Hirayama families.

Halling(38.098.012) used a rough model for gravitational compaction of a porous body and the Alfven-Arrhenius spin formula to explain the relationship between the spin frequency and diameter of minor planets. This relationship, derived by Dermott and Murray, has been refined(38.098.085), and the marked rise in rotation rate as the diameter decreases below 120 km seems not to be due to observational selection effects; they felt that the minimum rotation rate at 120 km may separate primordial objects from their collision products. On examining the possible stability of binary minor planets, Whipple and White(39.042.038) found extensive regions of bounded quasi-periodic motions and regions of bounded chaotic motion. Leone, Farinella, Paolicchi and Zappala(38.098.066) established that for objects of known rotational properties there are constraints on the admissible values of mass ratio and density and that such models permit a qualitative description of the expected light curve morphology. Binzel(40.098.013) showed that a binary model can explain the appearance of two distinct periods, 30.7 days and 7.90 hours, in the light curve of (1220) Crocus.

III COMETS

a) Discoveries, Recoveries and Astrometric Observations

During the interval, July 1984 – June 1987, 18 long-period and 14 short-period comets were discovered and 32 previously known short-period comets were recovered. Eleven of the discoveries were made by amateurs, often as a result of deliberate visual searches. All of the 21 discoveries by professionals were made on wide-field photographs; seven of them on films taken by Shoemaker and Shoemaker with the Palomar 0.46m Schmidt in search of unusual minor planets. Four comets were found on plates taken with the UK Schmidt, Siding Spring. Two of the newly discovered comets had initially received minor planet designations, 1984 JD = P/Kowal-Mrkos, 1984n, and 1986 UD = P/Urata-Niijima, 1986o. Another of the discoveries was made by Skiff(*IAUC* 4250) in the course of the UK-Caltech Asteroid Survey extension back to a plate taken by Kowal in 1977. Marsden recognized the identity of Skiff's object with one observed by Kosai with the Kiso Schmidt and recorded under the minor planet designation, 1977 DV3. P/Skiff-Kosai, 1976 XVI, proved to be of short-period with an unobserved return to perihelion in 1984. In additon three more sungrazing comets were found among data from the Solwind coronagraph; Solwind 4, 1981 XXI (observed on November 3/4, 1981, *IAUC* 4129), Solwind 5, 1984 XII (July 28, 1984, *IAUC* 4129 and 4230) and Solwind 6, 1983 XX (September 24/25, 1983, *IAUC* 4229). It is probable that all three are members of the Kreutz group of sungrazers. Perhaps the most interesting and surprising of the newly discovered periodic comets was P/Machholz, 1986e, a Jupiter family member with record small perihelion distance (0.13 AU) and record high incliation (60°).

The main contributors to recoveries of periodic comets were Gibson, who now uses the 1.5m reflector at Palomar with a CCD detector (14 recoveries during the triennium), Gehrels and Scotti of the Spacewatch program, which uses the 0.91m reflector of the Steward Observatory, Kitt Peak, with a CCD detector in a scanning mode (10 recoveries), and Gilmore and Kilmartin, who use the 0.6m reflector of the Mount John Observatory in a photographic mode (5 recoveries). The last program is particularly valuable for its coverage of the Southern Hemisphere. The promise reported at New Delhi General Assembly in 1985 for the Spacewatch system has been well borne out by more than 600 observations of 47 comets since regular operations began in January 1985. A description of the system and method of operation has been given by Gehrels et al.(41.036.172).

Interest in particular comets as potential targets for planned spacecraft exploration again led to unusually early recoveries for several objects, namely, P/Grigg-Skjellerup, 1986m, by Birkle with the 3.5m telescope at Calar Alto, P/Tempel 2, 1987g, by the Spacewatch program and P/d'Arrest, 1987k, by Meech and Jewitt with the 2.1m telescope at Kitt Peak. CCD detectors were used in all three recoveries. Kresak(*IAUC* 4234 and *Bull. Astron. Inst. Czech.*, 38, 65, 1987) identified observations by Pons in February 1808 as belonging to P/Grigg-Skjellerup. The recovery and in fact the only observations of P/Honda-Mrkos-Pajdusakova at its return in 1985 were made visually by Australian amateurs, Clark, Pearce and Athanasou(*IAUC* 4055).

Comets recovered on their critical first returns included P/Boethin, 1985n, P/Russell 1, 1985b, P/Giclas, 1985g, P/Wild 3, 1987e, P/Bus, 1987f, P/Howell, 1987h, and P/du Toit-Hartley, 1986q, which was recovered on the basis of a prediction from observations only in 1982. Four comets, for which predictions for first returns were available, were missed. Perihelion times for P/Tritton and P/Kowal 2 were uncertain by many days, because observed arcs at the discovery apparitions were short and in addition the latter was close to conjunction with the sun at perihelion. P/Haneda-Campos was badly placed and P/Schuster, which had some chance of recovery from the Northern Hemisphere in late 1985 or early 1986, also was missed. The limited field of CCD detectors presents problems for the recovery of comets subject to substantial positional uncertainty, while the current dedication of the Palomar 1.2m Schmidt to the Sky Survey II limits the availability of a valuable wide-field search capability for faint returning objects. On the other hand the Survey II is producing comet discoveries as did the first survey.

Observations of Comet Bowell, 1980b=1982 I, by Meech and Jewitt in early November 1986 and with the Spacewatch system in December 1986 set new records, as the heliocentric distance at the latest observation was 13.9AU, far exceeding that of Comet Stearns, 1927 IV, when last observed in 1931. Comet Bowell had been under observations for nearly seven years, a record long interval for a non-periodic comet. Nakano(38.103.033 and MPC 12025) identified several more observations of minor planets as actually referring to comets, including P/du Toit-Neujmin-Delporte in 1941, P/Smirnova-Chernykh in 1978 and 1981 and P/Urata-Niijima in 1986 as well as P/Whipple in 1925.

The report interval included the perihelion passages and spacecraft intercepts of both P/Halley and P/Giacobini–Zinner. Encouraged by the International Halley Watch, nearly 140 observatories participated in obtaining some 6000 astrometric observations of P/Halley. Some 28 observatories in the USSR contributed 2000 observations of P/Halley, as well as 600 observations of 22 other comets. More than 500 observations of P/Halley were made at the Perth Observatory alone. In addition to programs already referred to, substantial numbers of observations of other comets including important follow–up on discoveries as well as last observations came from Oak Ridge(McCrosky, Schwartz and Shao; more than 370 observations of some 50 comets), Lowell(Bowell, Skiff and Bus), Chamberlin(Everhart and Briggs), Klet(Mrkos and Vavrova), Geisei(Seki), as well as several other observatories in Japan, Kambah(Herald), Victoria(Balam and Tatum) and Cerro El Roble(Torres).

A new edition of the magnetic tape file of observations issued by the Minor Planet Center in June 1986 contained 25 533 observations of comets. Since October 1986 an IBM–PC–diskette version of the MPCs has been available in addition to the print version. The diskette contains the filed and sorted observations in the format of the magnetic tape as well as data and program to extract orbits in the format of the catalogue and to compute ephemerides. After a lapse Marsden (in some instances in collaboration with Green and Roemer) resumed publications of the RAS annual comet reports with issues appearing during the period of 1976–1984 inclusive(39.103.001–004, .032, 40.103.004, .047, 41.103.001 and 42.103.029). Andrienko and Karpenko continued the series of publications on physical characteristics of comets with data on comets observed in 1976–1980(39.102.005, 42.103.025, 38.103.039, .040 and 41.102.015). Some 41 numbers of the *Kiev Komet. Tsirk.*, Nos. 326–366) appeared during the triennium as Churymov became the chief editor following the death of Vsekhsvyatskij in 1984.

Ostro(40.098.089) reported on observations of four comets detected by radar; P/Encke, P/Grigg–Skjellerup and the two close–approach comets in 1983, IRAS–Araki–Alcock and Sugano–Saigusa–Fujikawa. In connection with spacecraft missions Roser(38.102.072) studied the accuracy of astrometric observations of comets over the past 200 years with special emphasis on the cases of P/Halley in 1759, 1835 and 1910. Svoren(39.103.008) and Pittich and Svoren(40.103.007) published details of positions of comets observed from the Skalnate Pleso Observatory in 1972–1975 and in 1976, respectively. De Sanctis, Ferreri and Zappala (39.103.025) likewise published positions of comets observed at Torino in October 1982 through June 1983. Zook, Fernandez and Grun(40.102.103) studied selection effects working against discovery of small comets. Radzievskij, Mamedov and Ivanov(39.102.050 and 40.102.101), by using the interval of observationability of comets as the best criterion of discovery probability, demonstrated a considerable prevalence of long–period comets with retrograde motion, and also analyzed the distribution of comets with longitude of perihelion and with perihelion distance.

b) Orbits and Ephemerides

As in the past preliminary and improved orbits and ephemerides for newly discovered comets have been determined at the Central Bureau for Astronomical Telegrams/Minor Planet Center(Marsden, Green and, from mid–1986, Nakano) and been published in the MPCs and on *IAU Circulars* as appropriate. Predictions for returning periodic comets have also been published routinely in the MPCs as well as in the *Handbook* of the British Astronomical Association, in the *Comet Handbook* of the Oriental Astronomical Association and elsewhere. Principal contributors for returning comets have been Nakano, Milbourn, Marsden and Kobayashi. Tabulations of orbital elements from new work were included as well in Marsden's RAS annual reports on comets referred above. The fifth edition of Marsden's *Catalogue of Cometary Orbits*(41.002.024), issued in January 1986 and intended to be complete for comets observed up to the end of December 1985, contains orbital data for 1187 cometary apparitions, referring to 748 individual comets, of which 135 are periodic and 85 were observed at two or more perihelion passages. For the first time this edition of the orbit catalogue was also officially issued in machine–readable form, both on magnetic tape and on a VAX/VMS or IBM–PC diskette.

Among the studies of periodic comets that link several apparitions, often with inclusion of non–gravitational forces, were the followings; P/Brooks 2 by Sekanina and Yeomans(40.103.281) and also by Evdokimov and Zaripova(42.103.122), P/Encke by Sitarski(*Acta Astron.*, **37**, (1), 1987), P/Grigg–Skjellerup by Sitarski(42.103.235), P/Tsuchinshan 1 and P/Tsuchinshan 2 by Szutowicz(42.103.027), P/Harrington and P/du Toit–Neujmin–Delporte by Forti(41.103.002), and the 'intermediate' comets, P/Pons–Brooks, P/Olbers, P/Brorsen–Metcalf and P/Westphal by Yeomans(41.103.039). Festou, Morando and Rocher(39.103.101), in a study of the motion of P/Crommelin, found that the orbit has been stable over an interval of 1100 years between AD 1000 and 2100 and probably even longer.

Marsden(40.102.055) reviewed the status of recent investigations of non-gravitational effects on the motion of comets and encouraged further studies based on thermal models of the nucleus. More recently Fanale and Savail(41.103.656) have improved their model of cometary gas and dust production with application to non-gravitational force components and nuclear radii, especially for P/Halley. Froeschle and Rickman (42.103.014 and 42.103.015) continued their investigations of non-gravitational forces on short-period comets based on thermal models of the nuclei by considering both low-obliquity and high-obliquity cases.

Sekanina(39.103.183) developed a precession model for the nucleus of P/Giacobini-Zinner, which is one of the 'erratic' comets evidencing irregularities in non-gravitational perturbations due to outgassing. The motion of this comet was also studied by Evdokimov(*Komet. Tsirk.* No. 327), who found a secular retardation prior to 1972 and a secular acceleration from 1972 to 1985. Sitarski(38.102.030) included non-gravitational terms in Marsden's form in recurrent power series integrations of the equations of motion with applications to P/Kearns-Kwee, Kopff, Wolf-Harrington and Grigg-Skjellerup as well as long-period comets, Burnham(1960 II) and Rudnicki(1967 I).

Emel'yanenko(40.102.124) studied the long-term orbital evolution of several comets affected by librations of the critical arguments in orbit resonance with Jupiter and investigated the mechanisms of capture into resonance and ejection from it. Everhart and Marsden(*Astron. J.*, 93, 753, 1987) calculated 'original' and 'future' reciprocal semimajor axes for 23 new osculating cometary orbits derived during 1982-86. Radzievskij and Tomanov(39.102.028, 40.102.107 and 41.102.056) published a statistical catalogue of the parameters of orbits of long-period comets by using the Laplacian coordinate system in connection with their studies of the origin and orbit evolution of comets. Mamedov and Radzievskij(42.002.104) also published a catalogue of orbital parameters of nearly parabolic comets.

Much effort went into improvements of the orbit of P/Halley in support of the spacecraft intercepts. Leading roles were by Yeomans on behalf of the International Halley Watch and by Batrakov, Belyaev, Medvedev and Chernetenko for the Soviet VEGA project. An independent study was made by Landgraf, who reduced a previously unused series of observations by Lamont in 1836 by extending the period of useful observations at that apparition by more than half a year(40.103.852). Landgraf also studied the effects of modeling a displacement of the center of light from the nucleus(41.103.613), which was also investigated by Sitarski(38.036.054) and was included by Yeomans and Batrakov et al. in their works.

In his comprehensive paper Landgraf(42.103.603) also considered alternate forms for presentation of non-gravitational effects. Sitarski and Ziolkowski(in *ESA Report* SP-250, 1986) looked into causes of the discordance of results obtained by different investigators in the long term motion of P/Halley, and concluded that secular variation of non-gravitational parameters has to be taken into account. Stephenson and Yau(39.103.921) published a comprehensive catalogue of Far Eastern observations of P/Halley and diagrams showing the computed path at all apparitions from 240 BC to AD 1368. Stephenson, Yau and Hunger(39.004.038) also identified observations of P/Halley at returns in both 164 BC and 87 BC among Babylonian texts in the British Museum. Yeomans, Rahe and Freitag(41.103.724) surveyed historical records of P/Halley starting from 240 BC and gave information on observations related to physical properties as well as ephemerides for each apparition.

Comprehensive results of the long-term evolution project were published by Carusi, Perozzi, Valsecchi and Kresak(41.003.008). Integrations of the orbits of 132 short-period comets, including planetary perturbations and extended over a time span of more than 800 years, permit the identification of long term processes such as temporary librations about orbital resonances and patterns at close planetary encounters. Because of limited accuracy of many reference orbits as well as omission of non-gravitational effects, results were not intended to represent accurately motions of individual comets.

In a study complementary to that of Carusi et al., Belyaev, Kresak, Pittich and Pushkarev compiled a *Calalogue of Short Period Comets*(*Astron. Inst. Slovak Acad. Sci.*, Bratislava, 1986) based on new integrations of the motions of all known short-period comets. In addition to planetary perturbations non-gravitational effects were included when possible (25% cases). Intervals of integrations, chosen to reflect the accuracy of initial orbits, range from 200 years for objects observed repeatedly to 50 years about the time of appearance of single-apparition comets. Additional information includes geometric observing conditions for each perihelion passage of individual comets, observational histories, lists of osculating elements at uniform 25 year intervals, close planetary encounters and the like. A variety of additional information is included in appendices.

c) Theoretical Investigations; Origin and Evolution.
Dynamics of Comets(ed. by Carusi and Valsecchi, 40.012.034), the proceedings of the IAU Colloquium No. 83, contains many papers reflecting current works on various aspects of cometary dynamics. In addition a comprehensive review of current views and topics of research interest in cometary dynamics was published by Weissman(40.102.112).

Ideas related to the origin of comets were reviewed by Bailey, Clube and Napier(41.102.051). Following an historical introduction they discussed the dominant issues of the middle years of this century and then surveyed the ideas that have arisen during the past decade, particularly, those related to the realization that the outer parts of the Oort cloud are not stable in the presence of galactic influences. Clube and Napier(39.102.064) considered comet formation in molecular clouds and the possibility of repeated cycles of capture and escape of comets as the solar system orbits in the Galaxy. Tomanov(37.102.011) discussed an interstellar origin of comets including condensation of nuclei in dense dust–gas clouds, capture by the solar system and planetary perturbations of cometary orbits. Hills(42.102.070) looked into formation of comets by radiation pressure in the outer part of a collapsing protosun, while Bailey(*Icarus*, **69**, 70, 1987) concluded that a high space density of comets could arise in molecular clouds through formation of comets in wind–driven shells around protostars. Weissman(41.102.008) addressed the question of primordial vs. episodic origin of comets as related to planet formation, by noting that primordial theories have generally gained wider acceptance. Festou(42.102.063) published a paper on origin of comets, and Oort(42.102.061) gave the Halley lecture for 1986 on the subject of the origin and dissolution of comets.

Weissman(in *The Galaxy and the Solar System*, ed. by Smoluchowski, Bahcall and Matthews, U. Ariz. Press, 1986) reviewed the dynamical effects of the galactic environment on the Oort cloud. Bailey(38.102.026) also studied origin of comets on the basis of structural characteristics of the Oort cloud, and concluded that a choice between a steady–state primordial model and a recent capture event, if based on $1/a$ distribution, depends on entirely on assumptions made about comet fading. Bailey(41.102.002) examined the implications for cometary origin in a study of the mean rate of energy transfer to comets in the Oort cloud, by considering perturbations by both stars and giant molecular clouds, and concluded that the majority of primordial comets beyond 10^4 AU are removed during the age of the solar system, and that solar nebula models, that more readily generate a massive inner core of comets, need to be investigated. Lust(38.102.044) studied the distribution of aphelion directions of long–period comets in several coordinate systems, and concluded that a systematic north–south asymmetry can be at least partly explained by observational bias and that a difference in behavior is evident between dynamically 'new' and 'intermediate' comets as compared with 'old' comets with smaller semimajor axes, but no evidence was found for a concentration of aphelia around the antapex. Schreur(40.102.006) studied the production of long–period comets as a result of stellar perturbations on cometary orbits.

The primary importance of galactic tides, particularly, vertical tides caused by the galactic disk, in defining the boudary of the solar system, was identified by Smoluchowski and Torbett(38.091.005), while Harrington(39.102.004) looked into the influence of galactic tides, particularly, the vertical tide, on the distribution of orbits of long–period comets. Heisler and Tremaine(41.102.042) studied the rate of orbital evolution of comets in the Oort cloud under the influence of the galactic tides, while Hut and Tremaine (40.102.003) derived formulae for the disruption rate of the Oort cloud due to encounters with interstellar clouds and field stars. Heisler, Tremaine and Alcock(*Icarus*, **70**, 269, 1987) looked into the frequency and intensity of comet showers that might be triggered by passages of stars near the sun, and supported the conclusion that the galactic tides, rather than individual stellar perturbations, are dominant in driving the evolution of the Oort cloud.

Mignard and Remy(40.102.018 and 40.102.019) have improved their models of the evolution of the Oort cloud under the influence of random passing stars, and concluded that the cloud is stable against such disturbances for the life of the solar system, but star passages can account for the present rate of appearance of new comets in the inner solar system. Byl(42.102.028) updated his earlier studies of the effects of galactic perturbations by using a more realistic galactic model. Torbett(42.102.025) examined the capture of interstellar comets approaching with the velocity of 20km/s through three–body interactions in the planetary system, and concluded that Jupiter is the only planet capable of scattering such comets into bound orbits and that with an observational upper limit on interstellar comets of $10^{13}/pc^3$ the capture rate amounts to only one comet every 60 years. Torbett(42.102.062) also looked into the ejection of Oort cloud comets into the inner solar system by galactic tidal effects.

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Bailey, McBreen and Ray(38.102.005) discussed several ways, in which limits on the mass of a possible dense inner core of comets surrounding the planetary system might be established observationally, and in which similar clouds surrounding nearby stars might be detected. Possible direct detection of the Oort cloud from submillimeter observations was discussed by Marochnik and Sholomnitskij(41.102.039). Mendis and Marconi(42.102.013) considered the implications for the total mass of comets in the solar system of possible formation of the Oort cloud by dynamical ejection from the Uranus–Neptune zone in the late phases of comet formation. If there is a substantial 'inner' Oort cloud, the total mass of comets in the solar system could approach one fiftieth of the solar mass.

Question related to possible periodic impact events and biological extinctions on the earth continued to give powerful stimulus to studies of the dynamical evolution of the Oort cloud and the ejection from it of comet showers, periodic or otherwise. The picture that has emerged is of a more massive cloud than formerly thought, smaller in extent, and possibly replenished from an inner cloud that may play a role as well in the inward diffusion and planetary capture of short–period comets. An historical perspective on extinctions and possible astronomical causes was given by Bailey, Wilkenson and Wolfendale(*Mon. Not. Roy. Astron. Soc.*, **227**, 863, 1987), who concluded, from an investigation of perturbations of the Oort cloud by known stars and molecular clouds, that comet showers induced by such processes are not likely to be the primary cause of a putative 30–Myr periodicity of impact phenomena in the terrestrial record. Fernandez and Ip(*Icarus*, **71**, 46, 1987) examined characteristics of comet showers that might be induced by close stellar encounters, and concluded that showers intense enough to be reflected in crater statistics could be produced at intervals of 80 Myr or so, provided that the Oort cloud has a massive core. In such a case the direction of approach of residual shower comets might be localized, possibly by explaining the clustering of aphelion points of long–period comets.

Stern(*Icarus*, **69**, 185, 1987) found that the influx rate of extra–solar comets, arising from encounters of the solar system with Oort–like comet clouds associated with passing stars, could have produced only a few impacts on terrestrial planets over the life of the solar system. Morris and Muller(41.102.041) studied the rate of infall of comets from the Oort cloud under the effects of the galactic tidal field, with the conclusion that the flux of comets into the inner solar system would be continuous and nearly isotropic, and would mask any possibility of determining trajectories of passing stars from analysis of the distribution of angular elements of new comets. Hills(40.107.005) concluded, from a study of the expected effects of passage of a hypothetical low–mass solar companion star(Nemesis) through the planetary system, that evident lack of damage to planetary orbits implies a low probability of any such object at the inner edge of the Oort cloud, and that limits also can be inferred on the space density of low–mass perturbers in the galactic disk.

Among investigations of the capture of comets into short–period orbits Kazantsev and Sherbaum (38.102.001 and 39.102.031) concluded that the distribution of orbits of short–period comets, according to the angular elements, can be explained by evolution under the influence of planets acting over substantial intervals of time. Bailey(42.102.069), in a study of the flux of near–parabolic comets into the inner solar system, found that the capture of short–period comets was more likely to be initiated by Uranus or possibly Saturn rather than Jupiter. Fernandez(37.102.050) studied the influence of physical processes such as sublimation and dynamical processes such as perturbations by Jupiter on the distribution of perihelion distances of short–period comets, and concluded that a combination of such effects may be adequate to account for the steep decrease in the number of short–period comets with small perihelion distances. In another study of the dynamical capture and physical decay of short–period comets Fernandez(40.102.119) concluded that the brightness behavior is not likely to be a good index to the physical lifetimes, because of build–up of a dust mantle that leads to at least temporary deactivation. Kresak(in *ESA Report*, SP–250, 433) discussed the implications of recent findings about the nucleus size and intermittent activity of P/Halley for the aging processes of other comets. Failure to observe several short–period comets at times, when they should have been bright and favorably placed, suggests that dormant phases interrupt periods of activity and that the concept of secular brightness decrease becomes meaningless in comparison with irregularities in activity on shorter time scales.

Rickman(40.102.048) reviewed various aspects of interrelations and distinctions between comets and minor planets, and concluded that there is a more substantial probability for Jupiter–family comets to develop into asteroidal objects than has previously been accepted. Hahn and Rickman(39.098.047) integrated the orbits of some 14 minor planets in cometary orbits (perihelion inside 1.7 AU and aphelion over 4 AU), ten of them discovered in the interval 1979–84, and found several kinds of orbital evolutions including stable asteroidal, stable libration about resonances and chaotic cometary. Davies(42.098.007) argued that the fewer-than-expected detections of Apollo-type minor planets by the IRAS, Infrared Astronomical Satellite, may actually have been of extinct comets, observationally selected, because of unusual characteristics. Hartmann, Tholen and Cruikshank(*Icarus*, **69**, 33, 1987) examined the relationship between active comets, 'extinct' comets and dark minor planets on the basis of dynamical characteristics and spectrophotometric data. A group of ten minor planets, suggested on pure dynamical grounds to be extinct comets, have spectrophotometric properties resembling those of the most distant minor planets. They suggest that dynamically identified 'extinct comet candidates' are indeed outer solar system objects, probably of cometary origin. Nazarchuk and Shul'man(40.102.128) modeled the evolution of a cometary nucleus in the solar radiation field, and concluded that comets with perihelion distances greater than 1.5 – 2 AU tend to evolve into minor planets. Radzievskij and Tomanov(39.102.034) calculated Tisserand constants with respect to major planets for 121 comets with period shorter than 200 years under the assumption of a possible genetic relationship between short-period comets and the asteroid belt.

IV SATELLITES

a) Observations

Pascu continued photographic observations with the 26-inch telescope of the U.S. Naval Observatory for satellites of Mars, the Galilean satellites of Jupiter and Saturn I-VIII. At the Leander McCormick Observatory and the Yale-Columbia Station at Mt. Stromlo, approximately 30 photographic exposures per year for brighter satellites of Saturn and of Neptune as well as approximately 60 exposures for Uranian and Jovian satellites were made in the years of 1984-1986, and the plates were measured and the results were transmitted to the JPL, although this observation program has now ended.

At the Bordeaux Observatory about 70 plates for Saturnian satellites I-VIII were secured with the 14-inch refractor by Dourneau, Dulou and Le Campion in 1981 and 1982(39.100.001). At the ESO, La Silla, 95 plates for Saturnian satellites I-VIII were taken with the 1.50m Danish reflector in 1981 and the results were published by Dourneau, Veillet, Dulou and Le Campion(41.100.016). Observations were also made there by using GPO in 1980 by Debehogne, Freitas, Mourad and Nunes(38.099.123) and in 1981 by Debehogne(39.099.061). Observations of Saturnian satellites in 1982 were published by Debehogne(39.100.032). Observations of Saturnian satellites made by Taylor and Sinclair in 1978, 1982 and 1983 at the Royal Greenwich Observatory were published(40.100.004).

At the Pulkovo Observatory the Galilean satellites of Jupiter were observed in 1986 with the 26-inch astrograph and the normal astrograph by taking 35 plates. A party of Pulkovo observers carried out observations at Ordubad with the lunar planet telescope(D=0.7m, F= 10.0m) and 108 plates for the Galilean satellites were taken in 1984, 1985 and 1986. In 1986 60 plates for Phobos and Deimos were obtained using the same instrument. The greater part of the observations has been processed. Tolbin published results of observations for Mars and its satellites made with the 26-inch refractor in 1982 (*Izv. Glav. Astron. Obs. Pulkovo*, N 203, 44-49, 1986) and those for Saturnian satellites in 1975(40.100.006). At the Nikolaev Observatory 36 plates for the Galilean satellites and 22 plates for Saturnian satellites were taken by using the zone astrograph and Voronenko and Gorel published observations of satellites of Jupiter and Saturn in 1980-1982(*R. Zh.* 12.51.112, 1986). At the Goloseevo Observatory 60 observations of Deimos made with an astrograph in 1980 were published by Sereda(*R. Zh.*, 10.51.85, 1986). At the Engelhardt Observatory 202 observations of six satellites of Saturn obtained with the astrograph in 1980 were published by Kitkin and Chugunov(41.100.053). Kitkin published 41 positions of Saturn III, VI and VIII obtained in 1982 with the 16-inch astrograph(*R. Zh.* 10.51.91, 1986), and also results of 177 observations of Saturnian satellites made with the same astrograph and at its Southern Station at Zelenchuk by using an astrograph in 1982-1984(41.100.058).

Observations of Miranda, Uranus V, were made by Viera-Martins, Veiga and Lazzaro(41.101.061) and a paper concerning the image processing techniques for position measurements of Uranian satellites was published by Viera-Martins, Carvalho and Veiga(*Rev. Mex. Astron. Astrof.*, **12**, 399, 1986). Pascu and Seidelmann continued astrometric and photometric observations with the Mark IV CCD Camera of the Space Telescope Widefield Planetary Camera Team on the 61-inch telescope at Flagstaff for Jupiter XIV, Saturn XII, XIII and XIV, Uranus I-V and Neptune I and II(39.101.021 and 41.101.033), and they with Schmidt, Santoro and Hers(*Astron. J.*, **93**, 963, 1987) published observations of Miranda, Uranus I.

Aksnes and Franklin(38.099.034 and *Sky and Telescope*, **69**, 116, 1985), Arlot(38.099.016) and Arlot and Rocher(38.099.115) published predictions for some 300 mutual events of the Galilean satelites in 1985–1986 and contributed to a world-wide observing program of at least 130 events. First results were published by Arlot et al.(*Suppl. aux Ann. Phys.*, **12**, fasc. 1, 1987 and 42.099.024), by Allen and Budding(41.099.058), by Coulson(*MNASSA*, **45**, 77, 1986) and by Grigor'eva, Egorov, Tejfel' and Kharitonova, who observed at Ashkhabad in 1985(*Astron. Tsirk.*, N 1444, 1–3, 1986 and *Astron. Tsirk.* N 1447, 3–5, 1987). Aksnes, Franklin and Magnusson(42.099.068) traced the source of a puzzling longitude discrepancy between pairs of mutual eclipses and occultations occurring close in time to the phase defects on the satellites.

Mutual events of Pluto–Charon system were predicted for 1986 and 1987 by Tholen(40.101.051) and by Tholen, Buie and Swift(*Astron. J.*, **93**, 244, 1987) and were observed by Binzel, Tholen, Tedesco, Buratti and Nelson(39.101.021). A model for the eclipse events was given by Dunbar and Tedesco(42.101.054) and an asymmetry appearing between eclipses and occultations was studied by Mulholland and Gustafson (*Astron. Astrophys.*, **171**, L5, 1987).

b) Comparison of Observations with Theories

In 1984 Arlot, Morando and Thuillot(42.099.046) analyzed eclipses of Jupiter I made between 1775 and 1802, which were recently discovered and collected by Delambre. Heliometric observations made from 1891 to 1906 for the Galilean satellites were compared with modern ephemerides by Arlot(42.099.046) and observations of occultations of the Galilean satellites by Jupiter were analyzed by Fairhead, Arlot and Thuillot(42.099.048) and catalogued by Fairhead, Arlot, Jannot and Thuillot(*Astron. Astrophys. Suppl. Series*, **68**, 81, 1987). Lieske studied the evolution of the Galilean satellites (tidal perturbations and secular changes in mean motions) and showed observational evidences from a large set of data(*Astron. Astrophys.*, **176**, 146, 1987). Kiseleva(39.099.089) analyzed observations made at Pulkovo for the Galilean satellites in 1904–1910. Kiseleva, Glebova and Mal'kova(41.099.004) compared over 600 positions of the Galilean satellites obtained at the Pulkovo Observatory in 1975–1979 with Sampson's theory and with Lieske's E–1 theory, and found that the standard deviation in positions does not exceed 0."10. In two papers by Lieske(41.099.001 and *Astron. Astrophys. Suppl. Series*, **63**, 143, 1986) a collection of the Galilean satellite eclipse observations made since 1651 is presented.

Batrakov and Nikol'skaya(*Byull. Inst. Theor. Astron.*, **15**, N 9, 534–537, 1986 and N 10, 583–586, 1987 and *Kinematika Fiz. Nebesn, Tel*, **3**, N 3, 94–96) improved the orbital elements of Saturnian satellites I–VII by using modern astrographic observations. The perturbations were derived for Saturn I and II by Struve's theory, for Saturn III–V by Sinclair's theory, and numerical theories were developed for Saturn VI and VII. New values for parameters of the theories were obtained for Saturn I–V and osculating elements of Saturn VI and VII were derived for a certain epoch. Tolbin(40.100.006) compared observations of seven Saturnian satellites made in 1975 with the 26–inch refractor of the Pulkovo Observatory with the ephemerides based on the results by Batrakov and Nikol'skaya, and found that the standard deviation in position relative to the planet is close to 0".2.

Bykova, Shikhalev and Yurga(39.100.023, 40.100.009 and 41.099.005) constructed a numerical theory of Phoebe, Saturn IX, and published the collection of processed observations of Phoebe in 1898–1981, and they also refined the orbit by using modern observations made in 1940–1976, the standard deviation being 1".0. They also investigated various perturbations including relativistic effects on the motions of outer satellites of Jupiter and Saturn.

Dourneau(*These de Doctorat, Universite de Bordeau*, 1987) analyzed observations made in 1980–1985 at Bordeau, Pic du Midi, ESO and CFH and fitted them with previous theories by Kozai, Rapaport(Saturn I–VI), Taylor(Saturn VII) and Sinclair(Saturn VIII). Taylor(38.100.068) compared observations made in 1967–1982 with theories, and Sinclair and Taylor(39.100.037) generated the orbits of Titan, Hyperion and Iapetus, Saturn VI–VIII, by both numerical integrations and analytical methods and by fitting them to astrometric observations made in 1967–1982.

Laskar and Jacobson compared earth–based observations with general theories of the Uranian satellites of Laskar, derived the masses of the satellits which agree within 15% errors with the Voyager results, and provided a new ephemeris of the satellites by including Voyager data. Tholen(40.101.043) analyzed 19 speckle interferometric observations of the satellite of Pluto and observations of a partial occultation of the satellite.

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c) Theoretical Studies.
Henrad(39.099.033) proposed a new method by applying Hamiltonian perturbation theories, which is valid for the large libration case of the Galilean satellites. Thuillot(39.099.032) gave a method for obtaining developments of the secular elements related to the pericenters and the nodes of the Galilean satellites with respect to variations of the dynamical parameters. Vu(*These de Doctorat, Observatoire de Paris*) developed an analytical theoy of motion of the Galilean satellites. Henrard and Lemaitre(*Icarus*, **69**, 266, 1987) made a perturbation treatment of the 2:1 Jovian resonance. Greenberg(*Icarus*, **70**, 334, 1987) studied evolutionary paths in deep resonance for the Galilean satellites. Campbell and Synnot(39.099.017) derived the gravity field in the Jovian system by using Pioneer and Voyager data. Goldstein and Jacobs (42.099.050) and Greenberg, Goldstein and Jacobs(42.099.052) studied the secular accelerations in the mean longitude of Io, Jupiter I, and observational evidences for the secular changes of the mean motions were investigated by Lieske(*Astron. Astrophys.*, **176**, 146, 1987).

Borenenko and Schmidt(*Astron. i Geodez, Tomsk*, **13**, 31–36, 1985) obtained a literal solution of the satellite case of the restricted problem of three bodies by means of averaging Lie transformations with accuracy up to the eleventh order with respect to the small parameter, which is the ratio of the mean motions of the sun and the satellite, and constructed analytical theories of Jupiter VI, VII and X. Bordovitsyna, Boronenko, Bykova and Chernitsov(41.099.002) developed numerical and analytical theories of outer satellites of Jupiter.

Salgado and Sessin(40.042.099) studied the 2:1 commensurability in the Enceladus–Dione system and Sato and Ferraz–Mello(40.042.100) studied the 2:1 resonance in the same system. Taylor, Sinclair and Message (*Astron. Astrophys.*, **181**, 383–390, 1987) made a spectral analysis of the residuals derived by fitting Woltjer's theory of Hyperion to the numerical integration by Sinclair and Taylor (1985), which was extended over 50 years.

Chugunov(41.100.055) gave the root–mean–square error of representation of observations by the theory developed earlier by the author for Saturn II–VI and described a possibility of extensive application of his theory. Chugunov, Stolyarov and Stolyarov(38.100.076, 38.100.078, 39.100.006, 39.100.020, 40.091.008, 40.091.017, 40.100.005, 41.099.045, *Differenz. Uravneniya u Prikl. Zadachi, Tula*, 8–9, 1986 and *Astron. i Geodez., Tomsk*, N 14, 103–107, 1986) gave a qualitative investigation of the solution of the mathematical models describing resonant motions of some of Saturnian satellites as well as satellites in other systems.

Lazzaro, Ferraz–Mello and Veillet(38.101.018) studied the famous Laplacian resonance relation among Uranian inner satellites. Lazzaro, Veillet and Viera–Martins(40.101.062) determined the orbital parameters of Miranda, Uranus I, from Laplacian resonance analysis and Lazzaro and Viera–Martins(41.101.062) made a period analysis of Laplacian resonance of the inner satellites of Uranus. Laskar(*Astron. Astrophys.*, **166**, 349, 1986) developed a general theory of the five main satellites of Uranus including the secular and short period terms.

Orlov and Chepurova(40.099.126) and Baturina(41.091.026) studied the problem of the solar perturbations, which are dominant in the motions of outer satellites. Kovalevsky(*Cel. Mech.*, **34**, 243, 1984) studied the effect of resonant planetary perturbations on the evolution of the orbit of a satellite driven by tidal forces. The existence of possible satellites of Mercury and Venus was examined by Rawal(*Earth, Moon and Planets*, **36**, 135, 1986).

An extensive review of satellite orbits and ephemerides was made by Ferraz–Mello(39.097.005) and a new compact representation of ephemerides was presented by Chapront and Vu(*Astron. Astrophys.*, **141**, 131, 1987). By using this representation method Arlot, Chapront, Ruatti and Vu(*Astron. Astrophys. Suppl. Series*, **65**, 383, 1986) published ephemerides of the main satellites of Jupiter, Saturn and Uranus.

d) Faint Satellites
Faint satellites of Saturn and Uranus, which were discovered a few years ago by ground–based and Voyager observations, have attracted much interests of astronomers, as most of them have peculiar dynamical properties. Namely, some of them are moving nearly on the same orbits with others, both faint and bright, either near equilateral–triangular points or with large libration amplitudes, and some are moving like shepherdings of nearby rings. And somebody argue that there are still fainter satellites, which could not been discovered even by Voyagers, in order to keep the shape of narrow ringlets with very sharp edges for long intervals of time.

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Synnot(*Icarus*, **58**, 178, 1984) reported on his estimates of orbital parameters and their uncertainties for faint satellites of Jupiter determined from Voyager imaging data. Aksnes(40.099.037) reviewed the orbital status of very faint Jovian and Saturnian satellites and their interactions with the planetary rings by using both ground-based and Voyager observations. Carussi, Roy and Valsecchi(42.100.001) discussed the stability of the Saturnian satellite system including faint satellites, which are in commensurable relations with other ones. Synnot(*Icarus*, **67**, 189, 1986) showed an evidence of the existence of further small satellites of Saturn in additon to those, whose orbits had been firmly established by the time of the Voyager 2 encounter with Saturn by using Voyager imaging data.

Agafonova and Drobyshevskij(40.099.019) discussed on the origin of irregular satellites of planets by the assumption of explosions of the massive envelopes of the Galilean satellites. Burns(in *Satellites*, ed. by Burns and Matthews, 117, 1986) analyzed orbital evolutions of satellites. Sinclair(38.100.002) examined the effects of orbital resonances on satellites in tadpole or horseshoe orbits relative to Mimas, Encelauds, Tethys and Dione, Saturn I–VI. Greenberg(38.100.143) reviewed extensively the orbital resonances among Saturnian satellites, which include fainter ones. Lissauer, Goldreich and Tremaine(41.100.009) discussed the orbital evolution of Janus–Epimetheus, which are coorbiting fainter satellites of Saturn due to torques from Saturnian rings. Henon and Petit(*Cel. Mech.*, 38, 67, 1986 and *Icarus*, **66**, 536, 1986) gave series expansions for encounter type solution of Hill's problem, and described the interaction of two small satellites, which were initially on circular orbits with slightly different radii.

e) Rings

Dynamics of ring systems are one of the most exciting topics in celestial mechanics, as the Pioneer and Voyager spacecrafts discovered very peculiar properties of the rings of Jupiter, Saturn and Uranus. There are still many puzzles in them, particularly, in narrow ringlets with sharp edges and with eccentric orbits, about which much more works should be done.

Borderies(39.100.018) recalled the observations concerning the opaque rings of Saturn and Uranus, and described a model, which represents the kinematics of these rings. Brahic(40.100.003) described the dynamical processes of Saturnian rings, and reviewed in *Planetary Rings* (ed. by Greenberg and Brahic, 1984) observations, theories and prolems related to the rings. Petit and Henon(*Astron. Astrophys.*, **173**, 389, 1987) made a numerical simulation for planetary rings.

Neptune arcs, whose discovery was reported by Hubbard(41.101.021) and Hubbard and Brahic(*Nature*, January, 1986), were discussed by Lissauer(40.101.055) with a shepherding model of arc rings and by Goldreich, Tremaine and Borderies(*Astron. J.*, **92**, 490, 1986). Gor'kavyj(39.100.042) and Gor'kavyj and Friedman(40.091.006) studied the problem of dynamics of particles in the planetary rings and stability of rings, and they(40.101.006, 41.101.042, 41.101.043, *Pis'ma Astron. Zh.*, **13**, N 3, 237–244, 1987) predicted existence of unknown satellites of Uranus on orbits close to those, which were subsequently found by using the observations made by Voyager 2, in order to explain the present ring structures.

Hill and Mendis(*Earth, Moon and Planets*, **36**, 11, 1986) studied the dynamical evolution of Saturn's E–ring. Pandey and Mahra(*Earth, Moon and Planets*, **37**, 147, 1987) reanalyzed the observations of occultations of MKE 31 by Neptune on September 12, 1983 and showed a possible ring system of Neptune. Goldreich and Porco(*Astron. J.*, **93**, 724 and 730, 1987) studied the shepherding of the Uranian rings by 1986U7 and 1986U8. Besides a method of perturbations for particle dynamics several approaches of non–linear density waves have been made to explain detailed structures of rings; for examples, by Chu, Yuan and Lissauer(*Astrophys. J.*, **291**, 356, 1985), by Chu, Dones, Lissauer, Yuan and Cuzzi(*Astrophys. J.*, **299**, 542, 1985), and by Borderies, Goldreich and Tremaine(*Icarus*, 68, 522, 1985).

V OCCULTATIONS

a) Identification of Upcoming Occultations

Computerized search for future occultations are being performed independently by three sets of investigators. Wasserman, Bowell and Millis at the Lowell Observatory have published predictions for 1986 and 1987(40.096.004) and predictions for 1988 and 1989 will appear in the 1987 November issue of the *Astron. J.* In these searches the ephemerides of all minor planets, whose angular diameters are expected to reach at least 0.08 arcsec during the search years, are compared with the positions of approximately 340 000 individual stars in the SAO, AGK3, Perth 70, Pleiades Postional and Lick Voyager Catalogues. Two new Lick Voyager catalogues covering the spacecraft's encounters with Uranus (11 765 stars) and Neptune (4527 stars) were completed by Klemola and Owens during the reporting period. Dunham of Silver Spring has performed searches for about 70 of larger minor planets using a composite catalogue containing all of the above catalogues plus the U.S. Naval Observatory XZ catalogue and various astrographic catalogues. Dunham has published annual summaries of predictions in the *Sky and Telescope*(39.096.001). A third set of predictions for events involving SAO and AGK3 stars only has been prepared by Goffin of Hoboken(38.098.103 and 40.098.098).

Predictions of close appulses by P/Halley and P/Giacobinni-Zinner were published by Bowell and Wasserman(39.103.047) and Bowell et al.(39.096.008). Dunham also computed predictions for these two objects. Attempts were made to observe certain events with the IUE spacecraft and with ground-based optical and radio telescopes. Few results of these efforts have been published. It appears that most optical observations did not succeed in detecting dimming of the stars involved. Mink and Klemola (40.096.002) identified stars to be occulted by Uranus, Neptune and Pluto in the interval, 1985 through 1990, by scanning plates taken with the 0.51m Carnegie Astrograph. Events found in this search include 54 occultations by the Uranus ring system, 24 occultations by Uranus, 22 occultations by Neptune and 10 occultations by Pluto. Killian and Dalton(40.096.016) identified stars to be occulted by Saturn's rings in the years, 1985 through 1991. Photometry of occultation candidate stars was published by French et al.(42.113.016), Covault and French(41.101.058), Bosh et al.(41.101.057) and Vilas and Mink(41.096.001).

b) Prediction Refinement

Klemola continued to provide precise positions based on photography with the 0.51m astrograph for use in last-minute refinement of occultation predictions. Additionally a new 0.46m astrograph at the Lowell Observatory(39.032.007) began to contribute to refinement efforts. The Perth Observatory, the Black Birch Observatory and the Bordeau transit circle also provided needed astrometry. Basic limitations on the potential accuracy of occultation predictions made by using conventional astrometric techniques were discussed by Kristensen(41.098.001).

The Commission 20 Working Group on Occultations has been reorganized to disseminate last-minute updates more efficiently. Coordinators have been designated in various parts of the world to channel information to observers quickly. A list of more favorable occultations was compiled for concentrated prediction effort in 1987. This approach has shown promise with three of the targeted minor planet occultations observed since 1987. The International Occultation Timing Association continues to play a major role in coordinating observational activity.

c) Observations

Occultation observers of planets and their rings have been more successful than those pursuing minor planet events. The one bright spot in the minor planet area was the effort to observe the 13 November 1984 occultation of BD+8^{o}471 by (1) Ceres. This event was observed photoelectrically at 13 sites in Mexico, Florida and the Caribbean by teams from U.S. and Mexican institutions. The observations permitted a precise determination of the size, shape and bulk density of Ceres. A paper discussing the results will appear in the November 1987 issue of *Icarus*. Other minor planet occultations observed with sufficient coverage to permit a size determination since the previous report involved (47) Aglaja on September 16, 1984(*Bull. Amer. Astron. Soc.* 16, 1027, 1984) and (129) Antigone on April 11, 1985(*Bull. Amer. Astron. Soc.* 18, 797, 1986). Recent occultations by (511) Davida, (10) Hygiea and (53) Kalypso were observed in New Zealand, the United States and the Soviet Union, respectively, but in each case observations were successful at too few sites to allow a definitive diameter determination. Better luck with the weather and more participating observers are badly needed.

Since the last report at least 5 occultations by Neptune have been observed. Evidence of incomplete ring arcs in the vicinity of the planet has been reported by several investigators(40.101.049, 41.101.004, 41.101.021 and 42.101.009). The observations also have yielded new results about the size, oblateness and atmospheric properties of Neptune(40.101.050, 42.101.057, Hubbard et al. *Icarus* in press, 1987 and Hubbard et al., *Astrophys. J.*, in press, 1988). Two occultations by the Uranian system in 1985 and one in 1987 were observed at multiple sites. Data of this type continue to be of use in refining dynamical models of the Uranian rings(42.101.010).

Y Kozai
The President of the Commission