ASTRONOMY FROM WIDE-FIELD IMAGING

Part Eight:

SOLAR SYSTEM SURVEYS

ASTEROID AND COMET SURVEYS

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ABSTRACT. Past surveys are described in the logical sequence of (1) comets visually, (2) asteroids visually, (3) asteroids photographically and (4) comets photographically. Plots show the evolution of asteroid surveys in terms of visual discovery magnitude and ecliptic latitude, and similarities and differences between surveys for the different types of body are discussed. The paper ends with a brief discussion of more recent discovery methods and some thoughts on the future.

1. Visual Surveys for Comets

Naked-eye observations of comets date back to antiquity. Chinese dynastic records contain numerous such reports and provide evidence of a rather continuous systematic naked-eye survey of the sky for unusual objects for almost three millennia, finally ending only with the emergence of Sun Yat-sen in 1911 (Ho & Ang 1970).

Systematic telescopic surveys for comets were initiated by Messier in the late 1750s in connection with his attempt to recover Halley's Comet. A comet is normally distinguished, particularly visually, first by its appearance and then by its motion. As soon as one reaches below the naked-eye limit, he finds that the sky is filled with stationary objects of diffuse appearance. To simplify his comet hunting, Messier needed to catalogue as many of these annoyances as he could. Others have subsequently added to his list, and the more successful hunters have carefully memorized the positions of hundreds of galaxies, star clusters and planetary nebulae so that they can concentrate on the most promising cometary suspects.

Méchain, Caroline Herschel and others later provided some competition for Messier, and the first quarter of the nineteenth century was dominated by the activity of Pons, whose record of at least 26 (and possibly as many as 37) visual discoveries will be difficult — but perhaps not impossible — to beat. European comet hunters later in the nineteenth century included Tempel; and prolific discoverers, notably Barnard and Brooks, also appeared in the United States. Recently, some of the most successful comet hunters have been located also in Japan and Australia, where Bill Bradfield is the supreme visual discoverer of the twentieth century. The left part of Table 1 lists the leading visual comet hunters of all time. Other highly successful comet hunters who are still actively searching include David Levy (with 7 discoveries), Don Machholz (6 discoveries), Tsutomu Seki (6), George Alcock (5) and Howard Brewington (4). Favored telescope apertures are 10 to 25 cm (both reflectors and refractors, the latter frequently in the

H. T. MacGillivray et al. (eds.), Astronomy from Wide-Field Imaging, 385–400.

form of binoculars) with favored magnifications of 15 to 30 times, but a few observers have used apertures of 40 cm or more and magnifications in excess of 50.

Table 1. Comet discoveries

Observer	Total	Years	Location	Total	Years
VISUAL			PHOTOGRAPHIC		
Pons	26	1801-1827	Palomar	87	1950-
Brooks	21	1883-1911	Siding Spring	25	1975-
Bradfield	16	1972-	Flagstaff	12	1932-1986
Barnard	15*	1881-1891	Bergedorf	11	1918-1975
Tempel	13	1860-1877	Bloemfontein	11	1941-1959
Swift	13	1862-1899	Johannesburg	10	1935-1949
Messier	12	1760-1798	Mt. Hamilton	9	1892-
Giacobini	12	1896-1907	Simeis	8	1913-1949
Honda	12	1940-1968	Harvard	8	1932-
Borrelly	11	1873-1912	Zimmerwald	7	1957-
Mrkos	11†	1947-1959	La Silla	6	1976-
Winnecke	10	1854-1877	Heidelberg	6	1904-1947
Peltier	10	1925-1954	Turku	6	1939-1944
Perrine	9	1895-1902	Piszkéstetö	5	1974-

* and 1 photographic 1892 † and 2 photographic 1984-1991

The total number given for each Observer or Location is the number actually involved in the currently accepted names of the comets. If the asteroid standard of crediting only the first discoverer were adopted, the Total would generally be less, by up to as much as 5. In a few instances the Total could be increased with cases where comet names have been changed or where there are supposed discoveries of comets for which orbits could not be computed.

Another recent review (Marsden 1993a) discusses the modi operandorum of comet hunters in more detail. A comparison of the situation a century ago and nowadays shows little change. Total magnitude 12 seems to be an effective limit for a visual discovery, and comets of tenth magnitude have been found at elongations $\varepsilon \sim 30°$ from the sun. Visual discoveries are nowadays usually made by amateur astronomers, and competition from the professional photographic surveys, which tend to be made near opposition, means that few visual discoveries are made at $\varepsilon > 90°$ and hardly any at $\varepsilon > 120°$.

For reasons that are not entirely clear, photographic searches at small ε have not been particularly successful — and since a majority of the comets discovered visually would have been very faint, at high ecliptic latitudes β or in the Milky Way when they were previously opposite the sun, it seems likely that there will continue to be visual discoveries at a rate of two to four per year for some time to come. The first photographic discovery of a comet was in 1892 (except for a comet recorded during a total solar eclipse ten years earlier), and the fraction of amateur discoveries has diminished from one out of two around 1930 to one out of three now (Marsden 1988).

It is often claimed that more comets are discovered (or are discoverable) to the west of the sun (i.e. in the morning sky) than to the east (in the evening sky). This claim is true, but it is important to realize that it applies to the sky as a whole. Unless they are very close to the earth (or are exhibiting anomalous brightness variations), comets do not change much in brightness near opposition, and the morning side is obviously favored for discovery because they will then generally be moving towards the evening side. At the elongations where comets are likely to be found visually this particular bias is not relevant.

2. Visual Surveys for Asteroids

In the case of asteroids there is the obvious complication of their stellar appearance and that at the brightness level of visual surveys it is necessary to contend with many more stars than galaxies and other diffuse objects.

As is well known, a meeting was organized by von Zach at Schröter's observatory in Lilienthal in September 1800 for the purpose of surveying for the planet supposed to exist between Mars and Jupiter. Twenty-four astronomers were assigned 15° arcs of the ecliptic and were to search within $|\beta| \sim 4°$ of these arcs. Although they realised that the search would not be easy, they felt that the missing planet, like Uranus 20 years earlier, would show a recognizable disk.

Before these 'celestial police' could get to work, Ceres had been discovered by an outsider. Piazzi was the first astronomer to recognise that independent stellar objects fainter than first magnitude or so might actually be in motion with respect to other stars. This was not only when he discovered Ceres, but also nine years before, when comparison of his own observations with those of Flamsteed and Bradley enabled him to establish that each component of 61 Cygni had an annual proper motion of 5". Previous experience with faint stellar objects that moved had been restricted to satellites in the systems of Jupiter, Saturn and Uranus. Unsuspected detections of Uranus had been made before Herschel discovered it, and when Lalande accidentally recorded Neptune on two nights in May 1795 while preparing a catalogue of 47,000 stars for his Histoire Céleste he attributed the difference in position to an error and pursued the matter no further. Piazzi, however, was engaged in a ten-year project of compiling a catalogue with much more accurate positions of only 6700 stars, and his meticulous observations, made with the most precise astrometric device then available (the 1.5 m vertical circle built for him by Ramsden), clearly showed him that Ceres had moved by some 5′ when it crossed the Palermo meridian the next night. Ceres, at $\beta = -3\overset{\circ}{.}1$, was of visual magnitude $V = 7.8$ (according to the modern magnitude formula for the object) and was found while its discoverer was looking for a star that Wollaston had erroneously stated as having been in Mayer's zodiacal catalogue.

Piazzi has sometimes been criticized for failing to ensure that other astronomers could observe Ceres and for tracking it himself for only six weeks (when illness interrupted him). Sicily was geographically and politically rather isolated at the time, however, and since Ceres was already well past opposition at discovery ($\varepsilon = 133°$), the fact that he did follow the object through its stationary point and almost to evening quadrature was more beneficial to the determinacy of Gauss' orbit solution than cases of asteroids observed for as long as three months centered on opposition. The point is that Piazzi's observations departed from a great circle by almost 1°, and Ceres was only $0\overset{\circ}{.}5$ from Gauss' prediction when it was recovered on its return to the morning sky after conjunction.

Olbers was a member of the celestial police, but his discovery of Pallas came as he was checking the positions of stars in the vicinity of Ceres at its next opposition in March 1802. Its apparent motion was evident to him over the course of 2 - 3 hours. That two of the three brightest asteroids should have been at $V \sim 7$ and within 7° of each other was a stroke of luck, but since Ceres and Pallas were then at $\beta = +17^\circ$ and $+13^\circ$, respectively, the limited latitude range specified by von Zach would have revealed neither of them.

Harding was also a member of the team, and his discovery of Juno at $\beta = -0\overset{\circ}{.}3$ was more in accord with the original search plan, as he recognized a star not in the Histoire Céleste. Olbers had realized that the orbits of Ceres and Pallas intersected just east of the equinox points, and when the discovery of Juno near the equinox in September 1804 seemed to confirm his hypothesis that the asteroids were fragments of a single object, he renewed his own search near these points. His amazing luck held with the discovery of Vesta, the brightest asteroid, within 1 day of the fifth anniversary of the discovery of Pallas and within 1° of Pallas' former position near 20 Virginis.

While Olbers' successes were rather fortuitous (although he did go to considerable trouble to familiarize himself with the stars in two particular regions), Harding's success was due to his extraordinary diligence in charting the sky. His seven-volume Atlas Novus Coelestis, completed in 1822, contained 60,000 stars. He then became involved with the Berlin Academy's even more extensive star-mapping project, also designed to assist searches for asteroids. Suggested by Bessel and supervised by Encke, and like von Zach's original proposal involving the cooperation of several astronomers, the Berlin Academy enterprise was to cover the general region of the ecliptic to ninth magnitude in fields 15° square. Harding completed his zone, Hora 15, by 1830, and it was the 1845 publication of one of Bremiker's zones, Hora 21, that permitted Galle and d'Arrest to make their discovery, just 30 km from this meeting room, of Neptune.

Hencke was using Hora 4 of the Berlin charts when he discovered the fifth asteroid, Astraea, in December 1845, more than 38 years after its predecessor, which was in fact then located only about 3° away. Hencke is said to have been searching for new asteroids for 15 years, and he noticed Astraea, at $\beta = -8\overset{\circ}{.}7$, as being directly between two charted stars some $0\overset{\circ}{.}7$ apart. Little more than 18 months then elapsed before he also found Hebe with the help of Hora 17; at $\beta = +19\overset{\circ}{.}2$, Hebe had a discovery latitude that was not exceeded until 1899.

Iris was the last asteroid to be as bright as $V = 8.5$ at discovery. Nevertheless, when Hind found it, just six weeks after the discovery of Hebe, he remarked that on beginning his asteroid search the previous November "the Berlin maps were employed as far as they extend, small stars of 9.10 or 10th magnitude, not marked on the maps, being inserted from time to time as they came under examination" (Hind 1847). Hind, observing in London, was the first person to find three asteroids, and he was still the leader when he withdrew from the work in 1854 with 10 out of the first 30. The tactic of adding further stars to the Berlin Academy charts was also followed by others, but these charts had really outlived their usefulness for asteroid searches before the last Hora was published in 1859. In any case, that year also saw the completion of the observations for the Bonner Durchmusterung, with its coverage of the whole sky north of the tropic of Capricorn.

Luther, director of the observatory at Bilk, near Düsseldorf, from 1851 and discoverer of (17) Thetis the following year, had previously succeeded Galle as assistant observer in Berlin and been the author of Hora 0. Six of Luther's total of 24 asteroids were found in this hour zone. Actually, they were all in a right-ascension range of ten minutes in this hour zone, and ten more were found in an antipodal zone of twice this width. It is unlikely that he searched in these small ranges because of a belief in the Olbers hypothesis, but it is reasonable that he should memorize the star fields in relatively small regions of the sky. The regions near the equinoxes, particularly the vernal equinox, are well known to be the most prolific for discoveries of asteroids because of the high galactic latitude and the meridian altitude and length of night at the temperate latitudes where most observatories are situated (Kresák & Klačka 1990), and Luther seems perhaps to have been the first to appreciate this point.

When Ferguson found (31) Euphrosyne at $V = 11.6$ in Washington in 1854 (the first asteroid discovery outside Europe), he did so because he was observing (13) Egeria, only 5′ away and 0.5 magnitude brighter. And in Paris, Chacornac found (33) while following up (32), discovered by his fellow townsman Goldschmidt in the same part of the sky two nights earlier. Many asteroid discoverers felt that there was really no solution but for them to make their own charts, and of necessity these new charts were very closely confined to the ecliptic. Although it netted him only six asteroids, Chacornac single-handedly carried out one of the most immense enterprises of this type. His 'Atlas of the Annals of the Paris Observatory', published in six volumes during 1860-1863, contained 60,000 stars to magnitude 13 in 36 fields 5° square, centered on the ecliptic and covering half of it. At Hamilton College, in New York state, C.H.F. Peters, the second most prolific visual discoverer of asteroids, attempted to chart stars to fainter than magnitude 14 within 30° of the ecliptic; twenty of these charts were published in 1882, and another 20 were completed, but were still unpublished, at his death in 1890, largely because of a legal battle with an assistant who claimed that the work was his.

Goldschmidt found (41) Daphne in 1856 when it was already near evening quadrature at $\varepsilon = 92°$. The object was followed for only four days — by far the shortest observed arc of the early asteroid discoveries. He thought he had recovered (41) the following year but instead found a new object that became (56) Melete. The new object was observed for only two weeks and was also lost until he made an extensive search in 1861. Luther accidentally found (41) again in 1862 in his vernal-equinox search region; for a while numbered (74), the 1862 object represented the first case of an identification of a lost asteroid.

Table 2 lists the faintest numbered asteroid at discovery known at any given time. (2) Pallas was brighter at discovery than (1) Ceres had been, so the first entry after Ceres is (3) Juno. (4) Vesta was brighter, so next comes (5) Astraea, fully 1.5 magnitudes fainter at discovery than Juno had been, the largest jump in the whole — surprisingly short — list. When Tuttle discovered (66) Maja at the Harvard College Observatory in 1861 (with the 38 cm refractor that was still then equal largest telescope in the world) he was penetrating 1.2 magnitudes fainter than (62) had been seven months earlier and setting a record that would hold for 20 years. Peters' first discovery, (72), was made while trying unsuccessfully to extend the arc of (66) to seven weeks and more, and — not surprisingly — (66) was lost.

By far the most successful visual discoverer of asteroids was Palisa, who as director of the Austro-Hungarian Naval Observatory in Pola (at the tip of the Istrian Peninsula) found 28 of them during an interval of less than seven years starting in 1874. A very careful search in 1876 allowed him to recover (66), which had been lost for what was then a record long time. At the end of 1880 he moved to Vienna and gained access to the 69 cm refractor, which he continued to use regularly in his asteroid work until shortly before his death in 1925. His first Viennese discovery, (220) Stephania, is the next entry after (66) in Table 2; it was observed for only 12 days, however, and not definitively re-identified for 51 years. Palisa registers in Table 2 five times, repeatedly stretching his own limit. When the photographic era was getting underway in 1892 Palisa made his eighty-third visual discovery and had been responsible for one out of four of all the asteroids known — a fraction that no observer would (or will) ever again exceed.

Table 2: Successive record-breaking faint discoveries

No.	Year	V	Observer	Location	Lost until
1	1801	7.8	Piazzi	Palermo	
3	1804	8.2	Harding	Lilienthal	
5	1845	9.7	Hencke	Driesen	
9	1848	9.8	Graham	Markree	
13	1850	10.1	de Gasparis	Naples	
16	1852	10.9	de Gasparis	Naples	
17	1852	11.1	Luther	Düsseldorf	
24	1853	11.4	de Gasparis	Naples	
31	1854	11.6	Ferguson	Washington	
34	1855	11.7	Chacornac	Paris	
53	1858	12.3	Luther	Düsseldorf	1862
62	1860	12.5	Förster	Berlin	
66	1861	13.7	Tuttle	Cambridge	1876
220	1881	13.8	Palisa	Vienna	1932
242	1884	14.2	Palisa	Vienna	
251	1885	14.3	Palisa	Vienna	
254	1886	14.5	Palisa	Vienna	
280	1888	14.8	Palisa	Vienna	
452	1899	15.1	Keeler	Mt. Hamilton	1981
473	1901	15.4	Wolf	Heidelberg	1987
650	1907	15.9	Kopff	Heidelberg	1950
659	1908	16.1	Wolf	Heidelberg	
878	1916	17.5	Nicholson	Mt. Wilson	1991
2211	1951	18.6	Cunningham	Mt. Wilson	
5148	1960	18.7	van Houten	Palomar	
2148	1976	18.9	West	La Silla	
3806	1981	19.3	Bus	Siding Spring	
4241	1981	19.9	Bus	Siding Spring	

Other early cases where asteroids were lost until rediscovered or re-identified many years later were (99) Dike (rediscovered 47 years after its original discovery), (132) Aethra (49 years) and (155) Scylla (not re-identified until 95 years after its discovery).

Chacornac's Parisian star-mapping project was continued by the brothers Henry in 1872. By 1884 three-quarters of the ecliptic had been mapped, and they discovered 14 asteroids in the process. They then had to attend to a part of the ecliptic that crossed the Milky Way and estimated the need to mark 15,000 to 18,000 stars on each chart. It was at this point that they took experimental 3-hour exposures with a 16 cm *f*/13 achromatic lens and obtained images of stars down to magnitude 12 on photographic plates covering 3° x 3°. The plates were of such excellent quality that the Paris Observatory proposed that the Henry brothers build a larger instrument: "On pourra à l'aide de cet instrument obtenir en une heure une Carte du ciel de la même dimension qu'une feuille de la Carte écliptique, qui exigerait per les procédés ordinaires plusieurs mois d'un travail assidu" (Mouchez 1884). In 1887 their 34 cm *f*/10 telescope was adopted as the prototype for the full-sky 'Carte du Ciel', the great international 'Astrographic Catalogue' project that removed the Henry brothers from further participation in asteroid surveys and took the better part of a century to complete.

3. Photographic Surveys for Asteroids

The first photographic discovery of an asteroid, (323) Brucia, was made by Max Wolf at his private observatory in Heidelberg in December 1891. This object was followed for only 12 days and then lost until 1923. Another of Wolf's very early discoveries, numbered and named (330) Adalberta, apparently on the basis of photographic data on only two nights, was shown a few years ago (West et al. 1982) to be two separate background stars, so the number and name were then transferred to another asteroid found by Wolf. Wolf soon perfected his procedure (Wolf 1895), which was to use two 15 cm lenses to obtain 60- to 80-minute exposures, partially overlapping in time and tracked at sidereal rate, of a region of the sky up to some 10° across. Unlike a visual discovery, and asteroid candidate would be found photographically by its motion. The trails would be detected, and the object's existence could be confirmed, when the plates were placed on top of each other on a light frame and examined with a hand magnifier. The 75 cm focal length of the lenses was thought to be too small to allow accurate measurement of the plates, so all the necessary astrometry was still performed micrometrically, generally with the help of Palisa and other astronomers elsewhere. Because the discoveries were coming more rapidly than the orbit computations (which, indeed, were often not forthcoming at all), a system of provisional designations had to be introduced, and it must be noted that the statistics in this review refer *only* to asteroids that have received permanent numbers. Many of Wolf's early plates were subsequently measured and collected for publication by Reinmuth (1953).

In September 1892 Charlois initiated a photographic patrol at Nice using a very similar lens. He was already known for his visual discoveries and estimated that it took him a total of five hours to find a new asteroid photographically (including perhaps a three-hour exposure), some 16 times faster than his earlier visual searches. Charlois continued to rely on his own micrometry, both for confirmation and for positions. When he discovered his ninety-ninth and last asteroid in 1904 Charlois was several ahead of Wolf.

Lick Observatory made an early entry into the photographic fray by utilizing the 91 cm Crossley reflector. While there is obvious interest in seeing how the asteroid rates increase as one goes to fainter limits, completeness and the necessary astrometric follow-up can thereby be severely compromised. It was not surprising that (452) Hamiltonia should be immediately lost (see Table 2), and in a similar exercise later with the Mount Wilson 1.5 m reflector (878) Mildred suffered the same fate. The Lick observing was not confined to low ecliptic latitudes. At $\beta = +33\overset{\circ}{.}8$, (445) Edna in 1899 finally exceeded the discovery latitude of (6) Hebe. Then, at $\beta = -39\overset{\circ}{.}2$ two years later, came (475) Ocllo. This first discovery of an asteroid in the southern hemisphere to be numbered was made with the 61 cm photographic telescope at the Harvard Observatory's station in Peru.

The Harvard telescope had been funded by a gift from Catherine Bruce, and it was she (for whom Wolf's first discovery was named) who also made it possible for Wolf to move his observatory to the top of the Königstuhl, overlooking Heidelberg, and to replace one of the 15 cm telescopes with a 40 cm astrograph. Wolf achieved his first century at the beginning of 1905, and he and the other Heidelberg participants, notably Reinmuth, assured that this program has since maintained the lead, with now 802 Heidelberg discoveries, or one out of seven of the 5632 asteroids numbered by the beginning of August 1993.

Follow-up had clearly become a problem by the start of this century, Pickering (1903) remarking that "of the five hundred asteroids so far discovered, sixty-eight have not been seen during the past five years, while the last observation of twenty-five of them was from ten to thirty-five years ago". Metcalf, the Massachusetts amateur astronomer who must rank among the half-dozen or so greatest amateurs of the twentieth century, began his own photographic patrol for asteroids with a 30 cm *f/7* lens and measuring engine of his own design in 1905. Although he discovered only 41 numbered asteroids, he took up Pickering's cause on the need for more cooperation among observers, pointing out that by tracking exposures at the apparent motions of the asteroids and allowing the star images to trail one can follow faint asteroids with quite modest equipment (the 'Trépied-Metcalf method').

One outcome of the very effective collaboration between Wolf and Palisa was the 210 Wolf-Palisa ecliptic charts (which were widely used by Metcalf, for example), and in 1905 Palisa successfully resumed his program of visual discoveries for 18 years more, amassing an astounding total of 121. His final visual discovery, (1073) Gellivara, had $V = 15.7$, and 19 of his discoveries were fainter than $V = 14.5$. Four of them, (724), (728), (730) and (1073) were effectively lost until some time after 1975. The sole remaining lost asteroid, (719) Albert, was a Palisa discovery in 1911; it was then as bright as $V = 13.8$, but its large and eccentric orbit renders favorable recovery possibilities infrequent.

Wolf's acquisition of a 0.7 m photographic reflector in 1906 helped alleviate the follow-up problem for Heidelberg discoveries, and Metcalf (1912) could say that "all but 16 of the 750 [asteroids] have been observed in the last ten years and the large majority of them in the last five years".

Important photographic programs for discovery and follow-up were initiated around the start of World War I in Johannesburg, Simeis (in the Crimea) and Hamburg-Bergedorf, and photographic capability was added to the micrometric program at Algiers. The Hamburg program was relatively small, lasting until the beginning of World War II (although Kohoutek began another program there in 1967), its most celebrated successes being Baade's discoveries of (944) Hidalgo (the first object classified as an asteroid with its aphelion significantly beyond the orbit of Jupiter) and (1036) Ganymede (the intrinsically brightest asteroid with its perihelion inside the orbit of Mars).

Further substantial programs got started in 1925 at Uccle (near Brussels), in 1929 in Flagstaff (in connection with the search that produced the discovery of Pluto) and in 1935 at Turku. The Turku effort, under the guidance of Väisälä, considered for the first time the balance of efficiency and need in securing observations that will yield a reliable orbit at a single opposition. The immense growth of discoveries during the 1930s and the general disruption caused by World War II enforced this point. The surveys that began in the U.S. around 1950 at Indiana's Goethe Link Observatory and at the McDonald Observatory, both using astrographs of aperture only 25 cm, particularly addressed the problem of this disruption and went a long way toward restoring and reviving the inventory of observation of early-numbered asteroids — and, in Indiana's case, adding many further discoveries.

General sky surveys initiated in the late 1940s were noteworthy for the discovery of several unusual asteroids, particularly some in the vicinity of the earth. There were six such discoveries during 1947-1950 by Wirtanen with the Lick 50 cm astrograph and four during 1949-1953 in the course of the National Geographic Society's Sky Survey with the 1.2 m Schmidt at Palomar; the first of the latter was Baade's discovery of (1566) Icarus, which until 1983 had the smallest perihelion distance for any asteroid known. The very extensive survey by the van Houtens in Leiden using Palomar 1.2 m Schmidt plates taken by Gehrels on 11 nights in September and October 1960 and essentially covering an 18° x 12° region to $V \sim 20.5$ (for a moving object) netted almost 2500 asteroids, of which 134 are now the principal designations of numbered asteroids. This original Palomar-Leiden survey was particularly designed to yield asteroids of the Trojan group leading Jupiter in its orbit by around 60°. Further Palomar-Leiden surveys of the leading Trojan point in 1973 (T-2) and of the following Trojan points in 1971 (T-1) and 1977 (T-3) have now been completed and have yielded 53 more numbered asteroids; there was also a two-night, leading-point survey in 1965. One of the aims of this experiment has been to establish whether there is an excess of asteroids at the leading Trojan point. This is extraordinarily difficult to do because of the difficulty of ensuring completeness to identical magnitude limits, but the preliminary result is that the leading Trojans are the more numerous by a factor of two and more strongly concentrated to the ecliptic (van Houten et al. 1991). Since the 1970s the Palomar effort has been dominated by the surveys by Helin and Shoemaker, mainly with the 46 cm Schmidt and for earth-approaching asteroids. Other asteroids are noted too, particularly the numerous Trojans found in the Shoemaker program, and in a general collaboration with the Lowell Observatory in Flagstaff to catalogue main-belt asteroids.

An intense survey for asteroids with the 40 cm *f*/4 double astrograph at the Crimean Astrophysical Observatory at Nauchnyj was begun under the direction of Chernykh in 1963 and has been conducted in earnest since 1966. The field size is 10° square, and since 1975 successive 90-minute exposures have been made with each lens. Within less than a year from now this program will surpass the Heidelberg program as leader in the discovery of numbered objects, although third-place Palomar is moving up more rapidly and should take first place rather soon afterward: there are 300 of the 1960 Palomar-Leiden Survey objects alone that have been identified at other oppositions, and numbering is only awaiting routine additional observations.

Table 3 lists the most successful efforts at asteroid discovery, on the left by individual for visual observations and on the right by institution for photographic. The visual magnitude V_{min} of the faintest photographic discovery at each site is shown.

Other search programs during the past few decades include those at the Purple Mountain Observatory (near Nanking) and Klet' (in southern Bohemia). It is also important to note that, although the Flagstaff observations date back to a discovery by Lowell, fully 93 percent of the Flagstaff discoveries indicated in Table 3 were made with the 33-cm 'Pluto' telescope under the leadership of Bowell since 1979. Although it has only produced 53 discoveries, the program carried out by Börngen as time permits with the Tautenburg 1.3 m Schmidt is valuable, its faintest discovery having $V = 18.6$. Wild has 78 numbered asteroids ($V_{min} = 16.5$) to his credit in connection with the supernova patrol conducted since 1961 with a 40 cm Schmidt at Zimmerwald, near Berne. In recent years, several Japanese amateur astronomers have been very active, although they are for the most part using both small-aperture and small-field instruments: noteworthy are the efforts at Kushiro (80 asteroids since 1987, $V_{min} = 16.9$) and Geisei (43 since 1981, $V_{min} = 17.5$).

The leading observatory for asteroid discovery in the southern hemisphere is currently the European Southern Observatory at La Silla, although the programs with the 1.2 m U.K. Schmidt at Siding Spring will very soon cause the original southern leader, Johannesburg, to fall into third place and may well encroach on the La Silla record. Some 61 percent of the La Silla discoveries have been made by Debehogne with the 40 cm GPO (Grande Prism Objectif) astrograph, and most of the remainder are discoveries with the 1 m Schmidt. Almost 68 percent of the Siding Spring discoveries were made by Bus in the course of the 'UCAS' survey in 1981 (which produced the two faintest entries in Table 2, discovered only one day apart) or the pilot surveys in 1978 and 1979. The remainder have mainly been found by McNaught in the course of his examination of sky-survey plates for unusual and earth-approaching objects. Among these is (5335) Damocles, which at $\beta = -70\overset{\circ}{.}9$ has the highest latitude of any visual or photographic asteroid discovery and an orbit that extends from that of Mars to beyond that of Uranus.

Table 3: Asteroid discoveries

Observer	**Total**	**Years**	V_{min}	**Location**	**Total**	**Years**	V_{min}
VISUAL				PHOTOGRAPHIC			
Palisa	121	1874-1923		Heidelberg	802	1891-1959	16.8
Peters	48	1861-1889		Nauchnyj	760	1966-	17.4
Charlois	27*	1887-1892		Palomar	582	1949-	18.7
Luther	24	1852-1890		Flagstaff	441	1907-1988	17.1
Watson	22	1863-1877		La Silla	212	1976-	18.9
Borrelly	18	1866-1894		Turku	192	1935-1953	16.1
Goldschmidt	14	1852-1861		Klet'	166	1978-	17.0
Hind	10	1847-1854		Simeis	148	1912-1953	16.3
de Gasparis	9	1849-1965		Johannesburg	147	1911-1970	15.8
Pogson	8	1856-1885		Siding Spring	143	1979-	19.9
Prosper Henry	7	1872-1878		Nice	129	1885-1955	16.1
Paul Henry	7	1872-1882		Uccle	129	1925-1961	16.6
Chacornac	6	1853-1860		Nanking	129	1955-1983	16.6
Perrotin	6	1874-1885		Goethe Link	108	1949-1966	16.9

* and 72 photographic 1892-1904

Figure 1 plots the computed values of V for all the numbered asteroids at discovery. For this purpose the dates are taken to be those of the observations defining the principal designations, not the years when linkages were found with observations at other oppositions or when the objects actually received their permanent numbers. It is interesting to see that the introduction of photography — and the hiatus in Palisa's visual discoveries — resulted in a general *brightening* of the discoveries until the employment of larger photographic instruments several years later. The faintest discoveries at a given time are documented in Table 2. At the opposite extreme, it is noted that bright main-belt objects like (532) Herculina and (704) Interamnia were not discovered until 1904 at $V = 9.1$ and 1910 at $V = 9.9$ respectively. The subsequent bright stragglers were unusual objects discovered near the earth — (1036) in 1924 at $V = 10.2$, (2102) Tantalus in 1975 at $V = 10.6$ and (4179) Toutatis in 1989 at $V = 11.6$. The successes of the busy years preceding World War II are evident, as is the almost complete cessation of activity in the latter apart of the war and the years following. The effects of the Palomar-Leiden and UCAS surveys are also very noticeable.

Figure 2 is a plot of the discovery values of β, some 56 percent of which are positive. Although several of the earliest asteroids to be found were surprisingly far from the ecliptic, it can be seen that when visual discoveries started in earnest, around 1850, the latitudes generally diminished to the range originally considered by von Zach and in the charts made by Chacornac and others. The latitudes remained exceptionally small until the use of photography easily

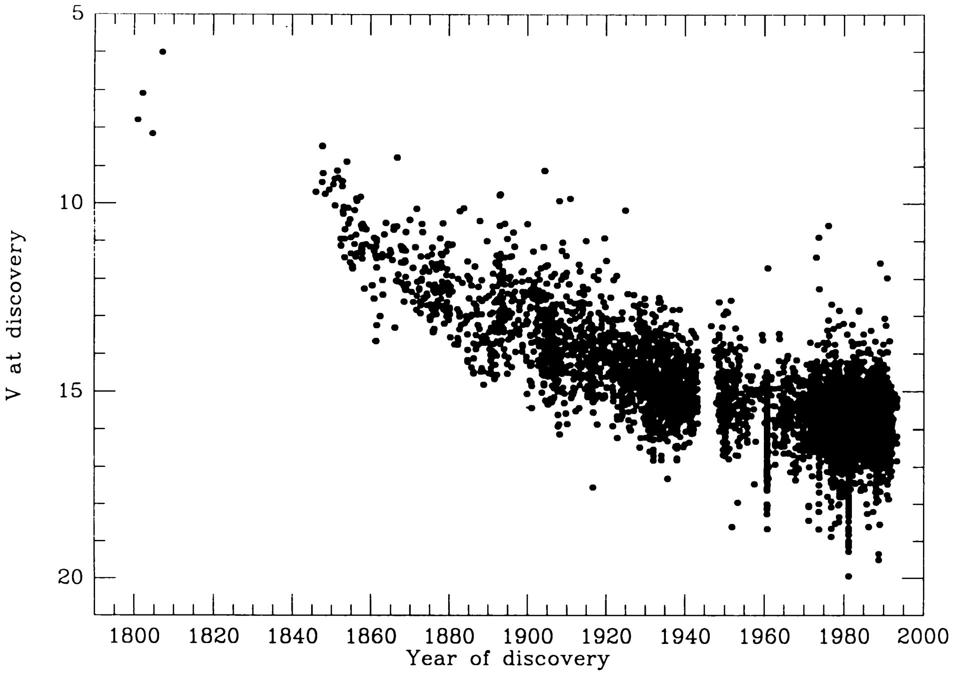

Figure 1. Plot of the computed *V* magnitude vs. discovery date for the 5632 numbered asteroids.

allowed a substantially wider range. Nevertheless, only 20.2 percent of the discoveries have been at |β| > 10° and only 3.8 percent at |β| > 20°. Even in recent times, there have been very few discoveries at more than 20° from the ecliptic, particularly on the southern side (70 percent of these higher latitudes being positive). High-latitude discoveries include (1373) by Hubble at Mt. Wilson in 1935 at β = +50°.8, (1917) at the Yale-Columbia station in 1966 at β = -58°.0, (3579) at the Budapest Observatory's Piszkéstető station in 1977 at β = +56°.7 and (3753) at Siding Spring in 1986 at β = -59°.8. The highest discovery latitude of all, +84°.0, is that of the Geminid parent and the asteroid currently of smallest known perihelion distance, (3200) Phaethon, which was discovered by the Infrared Astronomical Satellite IRAS in 1983.

Examination of the values of ε shows that only 0.3 percent of the asteroid discoveries have been made at elongations of less than 90°, 0.9 percent at less than 120° and 14.3 percent at less than 150°. Obviously, objects at |β| = 90° must also have ε = 90°, while those at |β| > 60° require 60° < ε < 120° and those at |β| > 30° require 30° < ε < 150°, but high-latitude discoveries are too infrequent to affect the statistics concerning elongation. Ten asteroid discoveries by West in 1976 were from a Schmidt exposure at the European Southern Observatory in 1976 that was centered at β ~ -8° and ε ~ 83° in the morning sky. The early detections allowed the objects, two of which were Trojans, to be followed through opposition and for up to six months; another new numbering (and a comet discovery) was achieved while West was following up one of the 1976 objects in early 1978 at ε ~ 70°. The smallest discovery elongation is 53°.5 in the case of (4349). which was found by Landgraf with the GPO astrograph

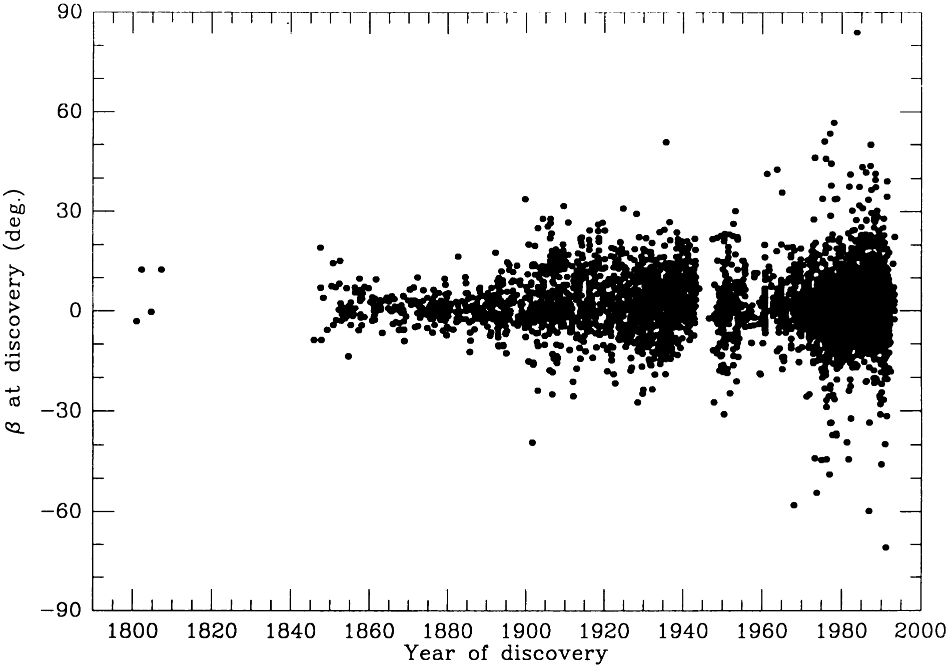

Figure 2. Plot of the computed ecliptic latitude β vs. discovery date for the 5632 numbered asteroids.

in 1989.

As has been discussed in the case of comets, there is obviously a bias toward discovery in the morning sky. For small discovery latitudes the fraction of number asteroids discovered in the morning sky is about 73 percent, and the median discovery longitude is some 8° east of the opposition point.

4. Photographic Surveys for Comets

There are no deliberate professional photographic surveys for comets. Many of the photographic discoveries of comets are made on the same wide-field exposures that also yield photographic discoveries for asteroids — the latter either by design, or as a by-product from sky patrols or supernova searches. The right hand part of Table 1 summarizes the photographic discovery statistics and, as in the case of asteroids, it does so by institution, rather than by individual. Many of the leading observatories are common to both lists, but there are differences, notably the failure of Crimea-Nauchnyj to make the comet list and the identification of several comets in the Harvard Sky Patrol and the southern patrol that Harvard conducted at Bloemfontein. The discoveries with the Schmidt telescopes at Palomar and Siding Spring clearly dominate.

The Palomar discoveries are equally divided between the 1.2 m and 46 cm Schmidts. If one includes the comet found in November 1949 that has recently been identified (Bowell 1992) with 'asteroid' (4015), there are a dozen comets from the original National Geographical Society Sky Survey during 1949-1955, and there have so far been ten since 1985 from the Second Sky Survey. Several other cometary images were subsequently detected on the prints from the original Sky Survey, but there could be no follow-up, and these are not included in the count. The first discovery with the smaller Schmidt was made by Helin in 1977 in the course of her near-earth-asteroid program. As of the end of 1992 there were 13 discoveries from this program and 29 (since 1983) from the Shoemaker program.

The Siding Spring discoveries are mainly from the southern sky survey, although one was made by McNaught using a small lens. As with the original Palomar Sky Survey, there are cometary images found too late for follow-up, although it was very recently possible to link together what were first announced as discrete detections in 1978 and 1979 (Marsden 1993b).

The faintest photographic comet discovery is perhaps Periodic Comet Tritton, estimated at about magnitude 20 on the Siding Spring 1.2 m Schmidt plates in 1978 and too faint and uncertain to be recovered at its subsequent returns. Some of the comets found with the 1.2 m Schmidt at Palomar, including a long-period comet from the original Sky Survey that was followed for two months in 1954, were described as of magnitude 19, and three of the faint cometary images subsequently identified on 1954-1955 prints were said to be of magnitude 19.5.

In the case of comets, the fraction of photographic discoveries made at small elongations from the sun in somewhat, but not excessively, greater than for asteroids, with 16 out of the 242 (7 percent) at $\varepsilon < 90^\circ$ and 48 (20 percent) at $\varepsilon < 120^\circ$ (Marsden 1993a). Much of the reason for this is, of course, that comets tend to be found at higher ecliptic latitudes than asteroids. Almost 13 percent of the photographic comet discoveries were made at $|\beta| > 40^\circ$ and more than 3 percent at $|\beta| > 60^\circ$, the highest latitude being $-78^\circ\!.7$ in the case of comet 1948 X.

As already noted, photographic discoveries at $\varepsilon < 90^\circ$ (the 16 including the record latitude case and five other comets with $|\beta| > 40^\circ$) have failed to compete with visual discoveries in this range. The faintest, the comet found by West in 1978, was of magnitude 17.5 at $\varepsilon = 71^\circ\!.8$ and has been discussed before (Marsden 1993a). Six other photographic discoveries in the range $59^\circ\!.8 < \varepsilon < 84^\circ\!.5$ were said to be of magnitude 13 - 15, i.e. fainter than the canonical magnitude limit of 12 for visual discoveries, but the comparison of visual and photographic total magnitudes is basically meaningless: one of the thirteenth-magnitude cases, comet 1989 XIX, was independently discovered 24 hours later by two visual observers who described it as brighter than magnitude 11!

5. Other Survey Methods

In addition to (3200) Phaethon, IRAS discovered six comets (two of which were independently detected from the ground) and one other asteroid that has so far been numbered. Operational constraints restricted their elongations to the range $86^\circ\!.7 < \varepsilon < 97^\circ\!.8$.

Sixteen comets at $\varepsilon < 4^\circ$ were discovered with the spaceborne SOLWIND and Solar Maximum Mission coronagraphs during 1979-1989 (Marsden 1989; MacQueen & St. Cyr 1990). All were approaching the sun and evidently close to it in space, and none seems to have survived perihelion passage or been observable from the ground.

Although CCD observation of asteroids began in 1984, when Gehrels initiated the first 'Spacewatch' survey with the Steward Observatory's old 91 cm reflector on Kitt Peak, and although the improvements completed in 1989 have sometimes resulted in the automatic recording of 2000 or more asteroids *each month*, the rate of numbering CCD discoveries has been extremely low. Spacewatch is designed mainly to study near-earth asteroids, and it is very efficient at finding very faint objects moving quite rapidly across the sky; but since the scan field is only 40′ wide (but 7°.5 long), only those unusual objects that are more distant, therefore intrinsically quite bright and rare, are likely to be followed up well enough to allow linkage with other oppositions. The six Spacewatch numberings comprise a Trojan, a Hilda (in 3/2 resonance with Jupiter), an object with a somewhat eccentric orbit in the outer part of the main belt, an Amor (with its orbit approaching but completely outside that of the earth), an Aten (with an orbit smaller than that of the earth); and (5145) Pholus, which has its perihelion near the orbit of Saturn and its aphelion beyond Neptune. Spacewatch has also found two comets, which at magnitudes 21 and 19 rank among the faintest recorded at discovery.

A seventh CCD asteroidal discovery has just been numbered. This is (5654) 1993 KG, found by the Italian amateur astronomer Vagnozzi and numberable because observations have been identified on several occasions extending back to the McDonald Sky Survey in 1951.

Two exciting new CCD discoveries of the past year have been very faint ($V \sim 23.5$) objects beyond Neptune, found by Jewitt and Luu with the 2.2 m reflector at Mauna Kea. The orbits of these objects (which have been given the provisional asteroidal designations 1992 QB_1 and 1993 FW, although it might be equally appropriate to regard them as cometary in nature) are still not fully determined, but it seems likely that their perihelia are sufficiently beyond Neptune to allow reasonable stability over the lifetime of the solar system.

6. Concluding Remarks

During the past decade photography has produced some 65 percent of the comets discovered (60 percent if one counts the SOLWIND and SMM sungrazers) and 99.7 percent of the asteroids that have received permanent numbers.

CCD techniques, which are responsible for some of the remaining numbered asteroids and a fraction of the comets, allow numerous detections of asteroids, but very few are currently followed up to the point where orbits are computed and they are eventually numbered. This state of affairs will presumably change as wide-field CCD capabilities become viable.

Amateur astronomers will continue to discover a significant fraction of the comets visually for the foreseeable future, particularly at elongations in the range $30° < \varepsilon < 60°$, to some extent to $\varepsilon \sim 90°$ and even to 120°. Visual opposition discoveries are rare.

Correspondingly, photographic discoveries are almost always at $\varepsilon > 90°$ and usually at $\varepsilon > 120°$, although several plates taken at small elongations with the 1.0 m Schmidt at Mérida during the past few years have been examined unsuccessfully (so far) for comets. Future CCD programs are also likely to encroach on the traditionally 'visual' elongations. Opposition searches now tend to be too restricted in latitude, particularly for $|\beta| \gtrsim 60°$. It can be noted that the maximum discovery latitude for a comet found in the Helin and Shoemaker near-earth-object programs at Palomar has been only +37°.1 (for comet 1989 V).

Searches for asteroids (nowadays necessarily photographic or CCD) are almost exclusively at $\varepsilon > 120°$. General coverage in discovery latitude has been largely restricted to $|\beta| \lesssim 20°$ since 1900. General coverage in magnitude has been largely restricted to $15 \lesssim V \lesssim 17$ since 1975. Massive searches, with appropriate follow-up, for objects that are fainter or are further from the ecliptic (or both), could presumably be effective for generating many more numbered asteroids.

The discovery of sungrazing comets clearly suffers from the absence since 1989 of an orbiting coronagraph capable of detecting them, and a new orbiting infrared observatory would be likely to produce comets generally, as well as unusual asteroids.

The discovery of transneptunian objects is a field that has scarcely entered its embryo stage. Like Luther before them, Jewitt and Luu have been concentrating on finding these objects close to the equinoxes. In an only slightly strained analogy with Olbers, they found the first two objects (which are nearly antipodal to each other) in the course of a search that had yet to cover one square degree of sky. The four-decade gap between the asteroidal discoveries of Olbers and of his successors shrank to a mere six months for this transneptunian population, with then the discovery in rapid succession of four more such objects, two again by Jewitt and Luu and two by a group using the 2.5 m Isaac Newton telescope on La Palma. Given the likely future accumulation of discoveries of these extremely faint objects and the need — because of their great distance — for monthly coverage beyond evening quadrature in order to obtain even a vague approximation to their orbital eccentricities, satisfactory follow-up is going to become a tremendously difficult problem. While it may well be that most of these new discoveries have stable orbits in the so-called Kuiper Belt, the observed transneptunian population can be complicated by the inclusion of near-aphelic detections of Pholus-type objects or 'Trojans' that may be associated with Neptune. When there were as many asteroids, just before the middle of the nineteenth century, the follow-up problem was much easier, for numerous telescopes were readily available for the astrometry, and orbital eccentricities could be derived from rather short arcs; even so, observations up to quadrature (by which time there was substantial fading) were always desirable for ensuring the recovery of a main-belt asteroid at its next opposition — contrary to the situation nowadays, where observed arcs are almost invariably quite short, and an asteroid is instead numbered on the basis of computations that yield identifications of the same object at other oppositions.

Acknowledgement

I thank Gareth Williams for preparing the figures showing the discovery magnitudes and latitudes for the numbered asteroids.

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