1

Historical Development

History shows you prospects by starlight.

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This first chapter is designed to give the reader an historical perspective on the subject of cataclysmic variable (CV) stars. Ground-based photometric and spectroscopic observational developments up to 1975 are treated in detail. Since that date instrumental methods in the optical region have been to some extent fixed, and to continue the historical approach would be repetitive of much of what appears in later chapters. The introduction of observational techniques in other wavelength regions is, however, followed beyond 1975.

1.1 Pre-1900 Observations of Novae

If the ancient philosophers had been correct in their assertion that the distant stars are immutable, incorruptible and eternal, astronomy would be the dullest of disciplines. Fortunately, they were wrong on all counts. The stars possess variability on all time scales and amplitudes, sufficient to satisfy all interests, from the exotic to the commonplace, from the plodding to the impatient.

Among these, the most prominent celestial discordants are the *novae stella*: *new stars*, challenging the ancients in their own times, but, such was the power of Aristotelian philosophy, passing almost entirely unacknowledged in European and Middle Eastern societies until the post-Copernican era (Clark & Stephenson 1977). In China, however, records of celestial events (kept mostly for astrological purposes) have been maintained since c. 1500 BC, and there are supporting and supplementary records in Japan from the seventh century AD and in Korea from c. 1000 AD (Clark & Stephenson 1976, 1977). Among these are numerous accounts of temporary objects, from which may be sifted comets, meteors, novae and supernovae.

Modern catalogues of ancient novae culled from Oriental records are given by Ho Peng Yoke (1962, 1970), Pskovski (1972) and Stephenson (1976, 1986). Earlier catalogues are listed in Payne-Gaposchkin (1957) and in Duerbeck (1987).

The supernovae of 1572 and 1604, comprehensively observed by Tycho Brahe and Johannes Kepler respectively, opened Western eyes to the mutability of the stars. The result, however, was hardly a flood of discoveries. Noting that there have been seven novae this century that reached magnitude 2.0 or brighter, and on the supposition that we do not live in particularly interesting times, it is a surprise, possibly even a scandal,

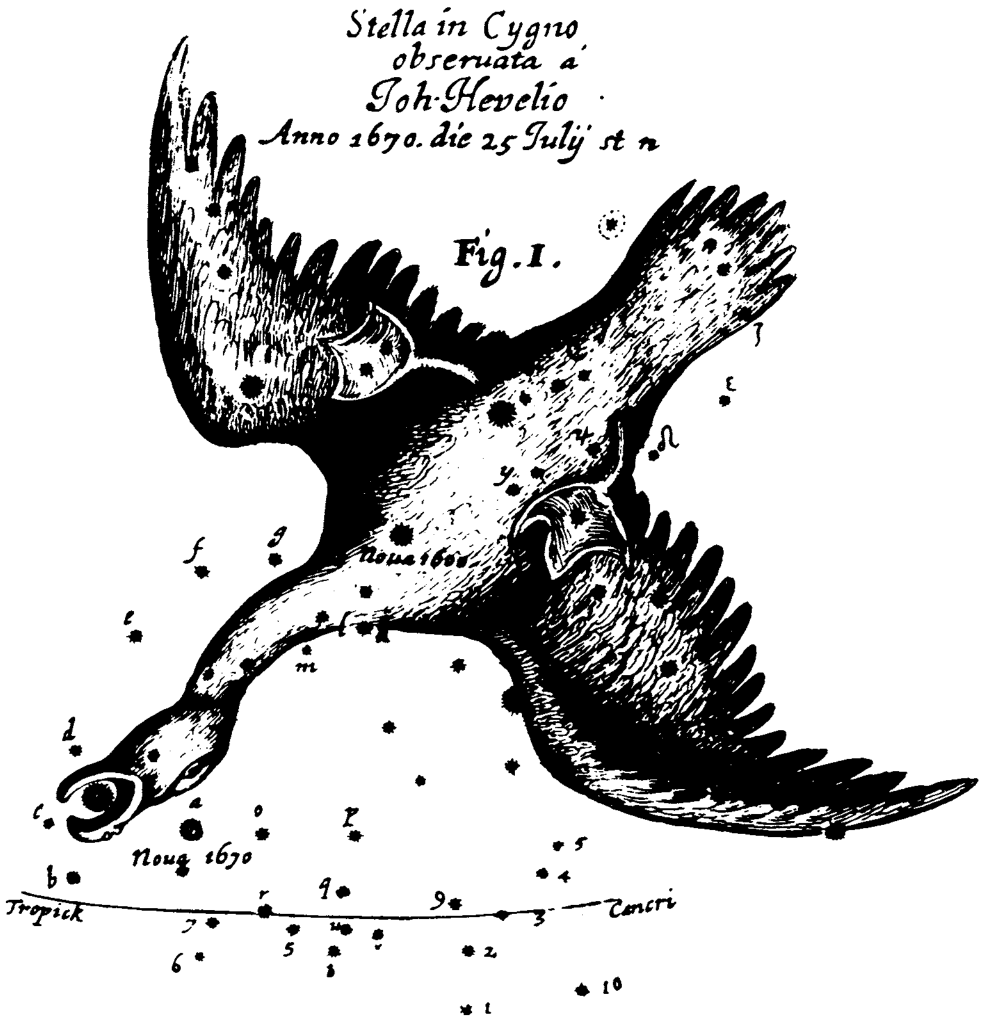

Figure 1.1 Chart of the constellation of Cygnus, published by Hevelius in 1670, showing the positions of Nova Vulpecula 1670 and 'Nova Cygni 1600' (now P Cygni). From Shara, Moffat & Webbink (1985).

to find that only one more nova was announced in the seventeenth century (the first true nova, as opposed to supernova, to be studied in Europe, discovered by the Carthusian monk Père Dom Anthelme in 1670 at second magnitude in the constellation Vulpecula: Figures 1.1 and 1.2), none in the whole of the eighteenth century and only one (Nova Ophuichi 1848) in the first half of the nineteenth century. (Some were *observed* during this time, and their positions measured, but were not *recognized* as novae at the time.) Before 1887, when novae began to be discovered on wide-field photographs of the sky, all but one of the half dozen novae found up to that time in the nineteenth century were the result of the steadily increasing activities of amateur astronomers.

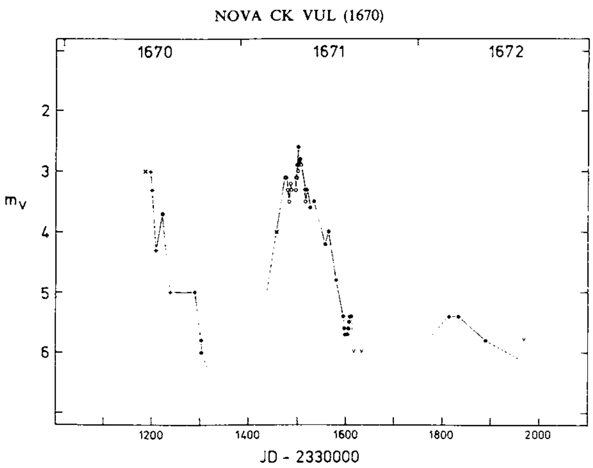

Figure 1.2 Light curve of Nova Vulpecula 1670 (CK Vul). From Shara, Moffat & Webbink (1985).

When John Russell Hind (1848) discovered Nova Oph 1848 it was the first such object to be publicly observable since 1670. Near its maximum brightness, Nova Oph was described as 'bright red' or 'scarlet' (Petersen 1848). This was during a long hiatus in the visual inspection of stellar spectra (Hearnshaw 1986), otherwise it would have been noted that the colour was due to intensely bright Hα emission. After eruption Nova Oph settled down to an easily-observable remnant of thirteenth magnitude: a unique object, at that time, as Nova Vul 1670 had faded to a level where it was unobservable.

The current status of pre-1900 novae can be found from the lists of Duerbeck (1987), Downes & Szkody (1989), and Downes & Shara (1993).

1.2 Discovery and Early Observations of Dwarf Novae

J.R. Hind, who was searching for minor planets near the ecliptic and only became a leading discoverer of variable stars *per adventure*, noted a previously unrecorded star of ninth magnitude 'shining with a very blue planetary light' on the night of 15 December 1855. After a patch of bad weather, it was observed still to be bright and in the same position nine days later, so Hind announced it as a new kind of variable star 'of a very interesting description, inasmuch as the minimum brightness appears to extend over a great part of the whole period, contrary to what happens with [the eclipsing binary] Algol and [the Mira variable] S Cancri' (Hind 1856).

Hind's confident statement about minimum light was based on the fact that he had been systematically searching this part of the sky for several years (during which in 1848 he discovered S Gem and T Gem) without previously having detected the new variable, soon designated U Geminorum. His comment on the blueness of the light of U Gem is very significant: a list of 53 variable stars known in 1856 shows that all except Nova Oph 1848 were Algol and Mira variables and hence either neutral or very red in colour (Pogson 1856). Thus U Gem was the first very hot, blue star to be studied by variable star observers; this caused some excitement over an apparent disc around the star, which was the result of optical aberrations – for a description of these and other aspects of early observations of U Gem see Warner (1986c). At minimum light, U Gem was found to be variable and just within reach of amateur telescopes at $m_v \sim 13$–14.

Three months after Hind's discovery, U Gem was found back at maximum light, this time by Pogson (1857), which proved that it was not an ordinary nova. From that time on during the nineteenth century U Gem was a favourite object among the leading amateurs, not least because of its rapid rise (less than one day) to maximum at unexpected times spaced anywhere from 60 to 250 days or more apart. Some observers followed it for over 30 years and left a mass of observations to be published posthumously (Knott 1896; Baxendell 1902; Turner 1906, 1907). The whole body of observations was discussed in a thesis by van der Bilt (1908), was the subject of one of the first harmonic analyses of light curves (Whittaker 1911; Gibb 1914), and caused Parkhurst (1897) to despair that 'Predictions with regard to it can better be made after the fact'. The early discovery of U Gem resulted in an almost continuously observed light curve (except for interference from the Sun for this ecliptic object) covering nearly 150 years.

Not until 1896 was another member of the class recognized, this time photographically, by Miss Louisa D. Wells on plates taken at Harvard College Observatory (Wells 1896). Varying from visual magnitude 7.7 to 12.4, and being far removed from the ecliptic, SS Cygni is one of the best studied of variable stars and, thanks in particular to the efforts of the American Association of Variable Star Observers (AAVSO), an almost continuous light curve from 1896 is available (Figure 1.3).

Belatedly, it was realized that T Leonis, discovered visually to be bright in 1865 by Peters (1865), and thought to be a nova, is also a member of the same class as U Gem and SS Cyg, known collectively, from their smaller amplitudes of outburst, as dwarf novae (this term was first used by Payne-Gaposchkin & Gaposchkin (1938), replacing the earlier term 'subnovae' used by Gerasimovic (1936)). Dwarf nova(e) will here be abbreviated to DN. In fact, T Leo is a member of the SU Ursa Majoris subclass, one of the three major subclasses of DN (U Gem and SS Cyg are representatives of another), which are described in Section 2.1.

The type star of the third subclass, Z Cameleopardalis, was next to be discovered (van Biesbroek 1904) and has been under continuous scrutiny since 1904 (Figure 1.4). The Z Cam stars proved stimulating as much for what they don't do as for what they do: they become stuck in an outburst state for unpredictable lengths of time.

The recognition of this new class of 'novae' resulted in distinguishing the original kind, of large amplitude, as classical novae (CN).

This is a suitable point at which to pay a tribute to the contributions made by amateur variable star organizations over the past century. Although most variable stars since the inception of wide-field photography have been discovered by professionals (a notable exception being bright novae), the responsibility of following the variations of the few hundred brightest irregular variables (Miras and other less regular red variables, novae and DN) has fallen to amateurs. Astronomy is an unusual science in that it is one in which the serious amateur can make not only useful discoveries but also long term measurements that have important statistical and interpretative value. Most

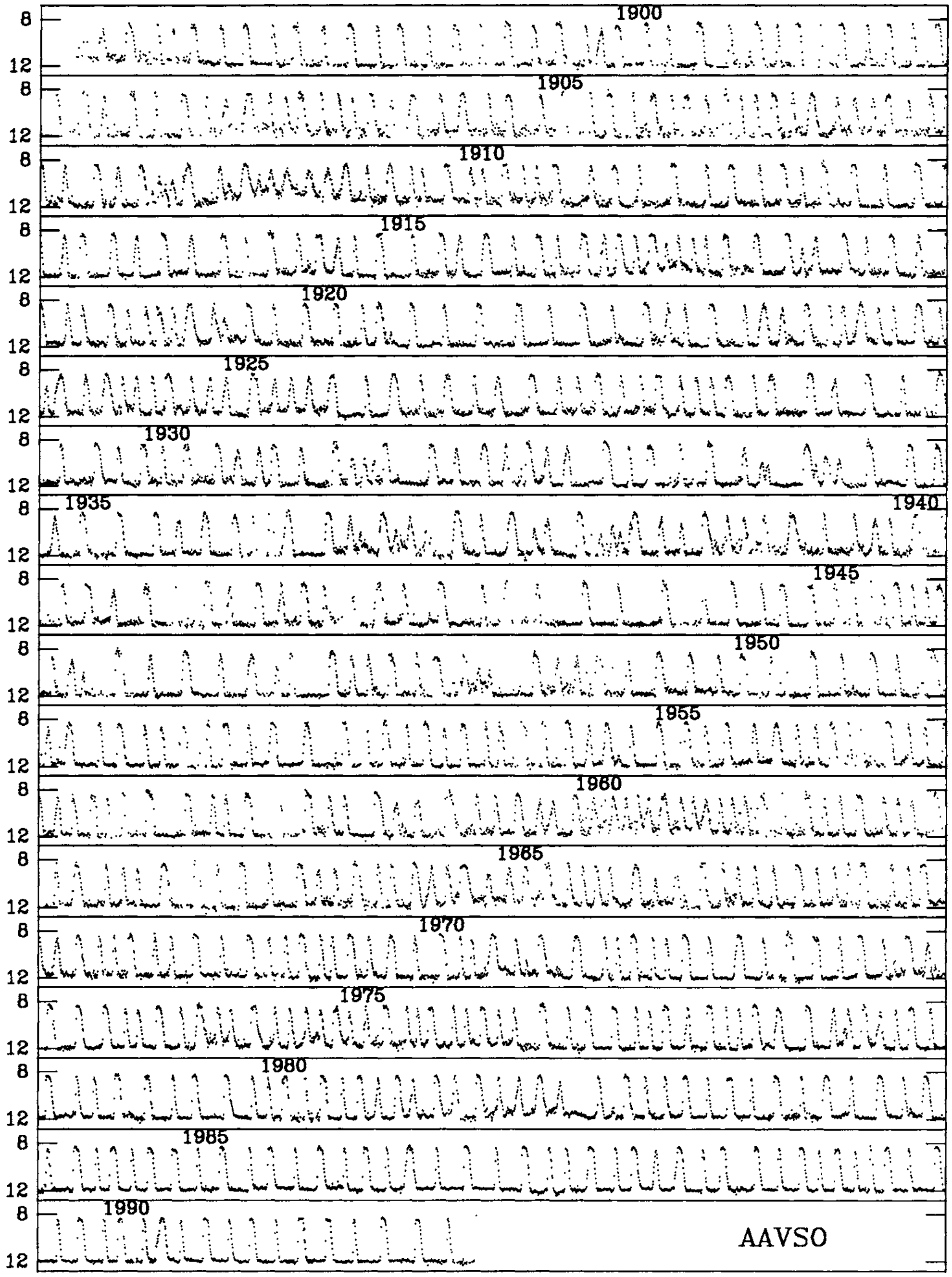

Figure 1.3 Light curve of SS Cyg, 1896–1992. The ordinate scale is visual magnitude. Constructed from observations made by the AAVSO. Courtesy J. Cannizzo.

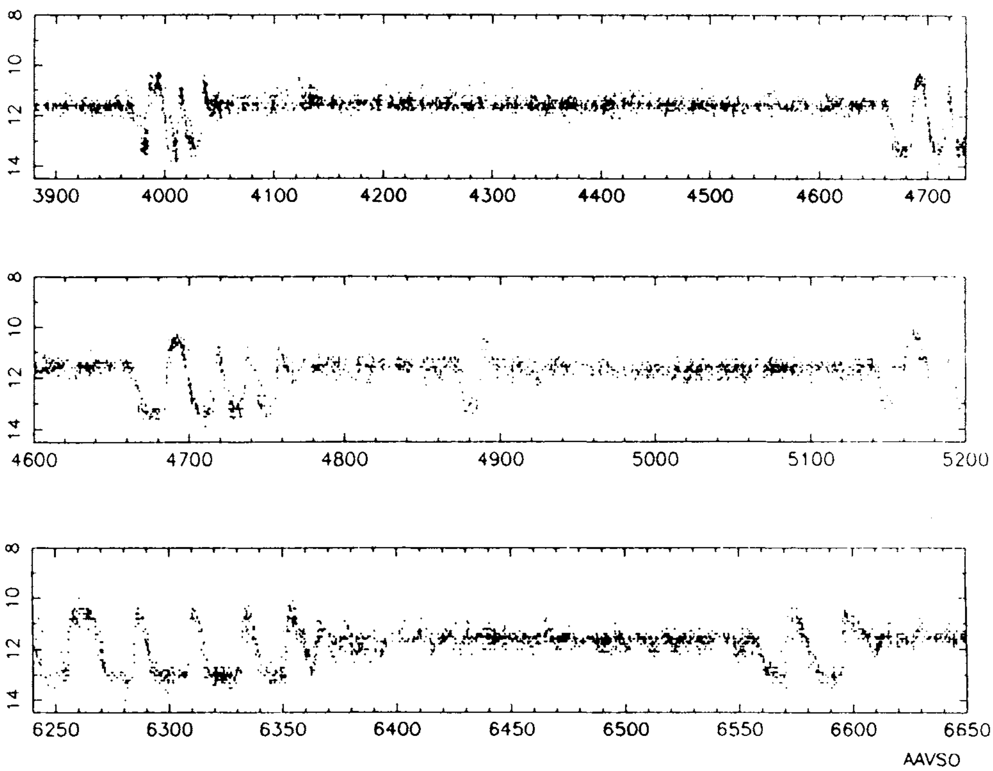

Figure 1.4 Light curves of Z Cam. The abscissa is Julian Date 2440000+; the ordinate is visual magnitude. From AAVSO observations. Courtesy J. Mattei.

of what is known about the long time scale behaviour of variable stars is derived from the concerted efforts of the amateur observers.

A crucial factor in the success of this effort has been international cooperation and central organisation, especially by the AAVSO (founded 1911) in the northern hemisphere and the Variable Star Section (founded 1927) of the Royal Astronomical Society of New Zealand in the southern hemisphere. Important long term contributions have also been made by members of the Variable Star Sections of the British Astronomical Association and the Astronomical Society of Southern Africa and also of the French Association of Observers of Variable Stars.

Thanks largely to the photographic surveys for variable stars carried out at the observatories at Harvard, Sonnenberg and Bamberg, by the time of the first edition of the General Catalogue of Variable Stars (GCVS: Kukarkin & Parenago 1948), of the 10912 variables listed, 108 were CN of various kinds, 92 were DN and 31 were nova-like (NL: see Chapter 4). By the fourth edition (1987), of 28 237 definite variables (there are thousands of suspected variables), 208 were CN, 342 were classified DN and about 35 NL (of a more restricted definition). These constitute the class of CVs that is the subject of this book.

A catalogue of 751 CVs, comprising 256 CN, 349 DN, 98 NLs (of a variety of types) and 48 unclassified, with accurate positions and finding charts, is given by Downes & Shara (1993). Charts for CN are found in Duerbeck (1987).

1.3 Photoelectric Photometry 1940–75

With the introduction of the 1P21 photomultiplier in the mid-1940s, photoelectric photometry gained sufficient sensitivity to bring many CVs within reach. The pioneering study was made by A.P. Linnell in February 1949 with the 61-in reflector of the Harvard Observatory's Oak Ridge station (Linnell 1949, 1950). The target, UX UMa, was known at that time as the shortest period eclipsing binary, with orbital period $P_{\rm orb} = 4$ h 43 min. It was not yet recognised in the GCVS as a NL.

Linnell's first observations (Figure 1.5) showed immediately the presence of intrinsic variation with amplitudes 0.01–0.2 mag on time scales from less than a minute up to several minutes, which were soon to be recognized as a characteristic of CVs (except for novae and some DN near maximum of outburst). Such *flickering*, as it was later to be termed, had been seen visually in 1946 in the recurrent nova T CrB (Petit 1946), in 1947 in the NL AE Aqr (then classified as a U Gem star) by K. Henize (1949) with the 26-in refractor at the Leander McCormick Observatory and by A.D. Thackeray and colleagues in 1949 in the NL VV Pup with the 74-in Radcliffe reflector (Thackeray, Wesselink & Oosterhoff 1950; see Section 6.3.3).

A second property discovered by Linnell, and commonly seen among other eclipsing CVs, was the variability of eclipse profile; in particular, the presence of a standstill of various lengths (or a shallower slope) on the emergent branch of the eclipse. The light curve also possessed a broad hump, lasting for about half of $P_{\rm orb}$, approximately centred on eclipse. Linnell proposed that 'a hot spot on the advancing hemisphere of the bright star' might account for the hump and eclipse profile.

UX UMa was observed further in 1952–53 by Johnson, Perkins & Hiltner (1954) and then both spectroscopically and photometrically by Walker & Herbig (1954). Their light curve (Figure 1.6) is characteristic of most CV light curves during the era of dc photometry and chart recorders over the period 1950–68. The model proposed for UX UMa by Walker & Herbig, consisting of 'a mass of hot material situated well above the surface of the primary...located asymmetrically with respect to the line joining the two stars', was an important step in the understanding of CVs.

At the same time, M.F. Walker carried out a photometric survey of CVs, stimulated by his discovery (Walker 1954a) of large amplitude flickering (up to 0.4 mag in 5 min) in the NL MacRae +43° 1 (now designated MV Lyr), in which rapid brightness variations were found in thirteen nova remnants, three NLs, four DN and a recurrent nova. During this survey, Walker (1954b) discovered that the remnant of Nova Herculis 1934, DQ Her, is an eclipsing binary with a light curve similar to that of UX UMa but with a slightly shorter orbital period of 4 h 39 min. Added to the discovery by Joy (1943, 1954a,b, 1956: Section 1.4.2) that AE Aqr and the DN SS Cyg and RU Peg are spectroscopic binaries, the evidence began to mount that all CVs are short period binaries and that flickering is in some way connected with their duplicity (Walker 1957).

An observation that was perplexing at the time but was to be of significance in the interpretation of DN was the series of light curves obtained by Grant (1955) during a 3-mag outburst of SS Cyg in which he found that, measured in intensity units, there is no increase in the amplitude of flickering during outburst: the outburst is an addition of non-flickering light to the flickering source at quiescence. Pinto & Rosino (1959) confirmed this and found that the flickering amplitude increases towards shorter wavelengths.

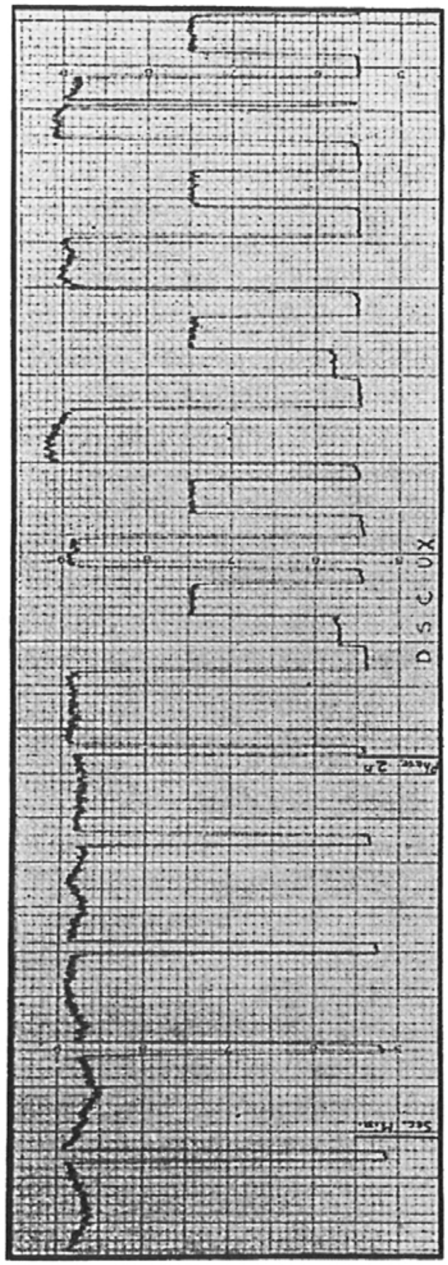

Figure 1.5 Chart recorder plot showing rapid brightness variations in UX UMa on 23–24 February 1949. Downward deflections are measurements of dark current, sky and comparison star. From Linnell (1949).

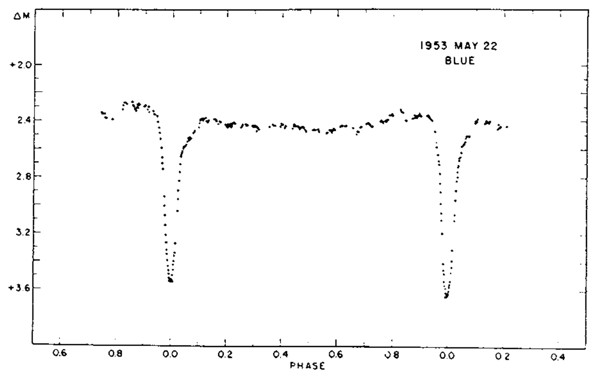

Figure 1.6 Light curve of UX UMa. B magnitudes measured every 0.5 min. The ordinate scale is the magnitude difference from a comparison star. From Walker & Herbig (1954).

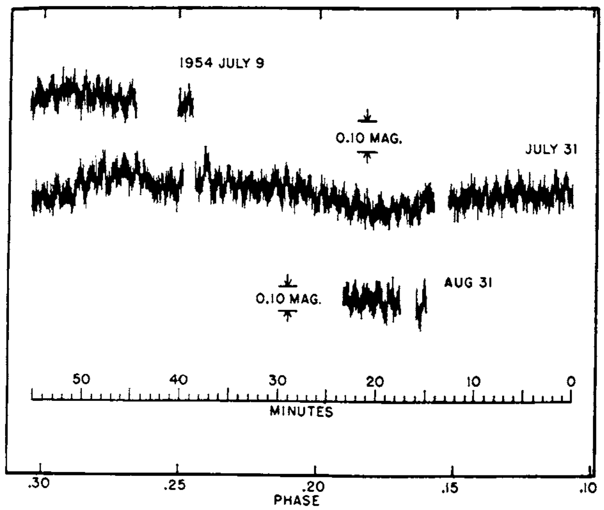

Figure 1.7 Discovery tracings of the 71 s brightness modulation in DQ Her (remnant of Nova Her 1934). The abscissa is orbital phase. From Walker (1956).

By far the most spectacular discovery to be made during Walker's survey was that DQ Her, as well as possessing flickering, shows a strictly periodic brightness modulation with a period of 71.1 s and an amplitude in the U photometric band of 0.070 mag (Walker 1956; Figure 1.7). Despite a search for similar periodicities in other CVs (Walker 1957; Mumford 1966, 1967a), it remained a unique phenomenon until technological improvements in photometry revealed further examples in the 1970s (Section 8.6).

To a large extent, the contribution of photometry during the decade following Walker's survey was simply the discovery of more eclipsing systems. By 1967, 23 CVs had known orbital periods, ranging from 82 min to 227 d, of which 19 were spectroscopic binaries and 13 were eclipsing systems (Mumford 1967a).

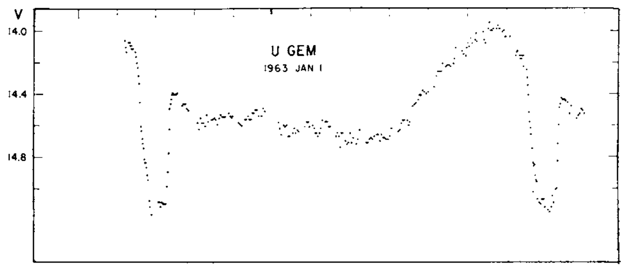

Figure 1.8 Light curve of U Gem at 0.5 min resolution. The orbital period (time between mid-eclipses) is 4 h 15 m. Adapted from Krzeminski (1965).

The most comprehensive study of a DN was that of U Gem by Krzeminski (1965). He obtained 4500 UBV measurements with a time resolution $\sim \frac{1}{2}$ min. At minimum light, U Gem showed eclipses superimposed on an orbital hump (Figure 1.8). His model for U Gem, similar to that for UX UMa, was that the hump arises from the varying aspects of a bright spot on the primary. Krzeminski's discovery that during outbursts the eclipses in U Gem become shallower and disappear at maximum, seemed to be interpretable in only one way: the seat of the outburst must be the orbital companion, not the hot primary as hitherto supposed. Further systematic effects – an increase in eclipse width during rise to maximum light and a concomitant shift in orbital phase of mid-eclipse – were interpreted as an asymmetrical expansion of the secondary star. Theoretical reasons were quickly found (Paczynski 1965a; Bath 1969) why the secondary of a close binary system could be unstable and be liable to occasional dramatic increases in luminosity.

Statistical studies of CVs by Luyten & Hughes (1965) and Kraft & Luyten (1965) showed that nova remnants have absolute visual magnitudes $M_v \approx 4$ and DN at quiescence have $M_v \approx 7.5$. They concluded that the hot primary components of CV binaries must be either white dwarfs or hot subdwarfs, confirming an earlier conclusion by Kukarkin & Parenago (1934) based on proper motions of SS Cyg and U Gem only.

The development of high speed pulse-counting photometry, reviewed in detail in Warner (1988b), revitalized the study of CVs and led rapidly to an improvement in the basic model for CVs (Warner & Nather 1971; and, independently, the same model from a different set of arguments by Smak 1971a). The realization that the hump in the light curve of U Gem lasts for at most 0.515 of P_{orb} showed that the longitudinal extent of the bright spot is no more than ~5°, which would require that its eclipse be very sudden (a few seconds) if located on the white dwarf primary. Furthermore, the high time resolution (2 s) photometry demonstrated that the amplitude of flickering is modulated in the same way as the light curve, being greatest at the maximum of the orbital hump, which implied that the flickering originates in the bright spot. The fact that flickering disappears during eclipse (Figure 1.9) showed that the hot spot is certainly eclipsed. Consequently, it was realized that *it is the accretion disc itself which brightens during a DN outburst* and that in U Gem eclipses are of a bright spot located on the outer edge of the accretion disc, where the stream of gas from the secondary impacts on the disc (Figure 1.10). The inclination in U Gem is such that most of the