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激变变星的多波段研究 (I)

邓世兵　陈建生
(中国科学院北京天文台　北京　100080)
马骏
(中国科学院空间研究中心　北京　100080)

摘　要

最近十年来，无论是在观测上还是在理论上，人们对激变变星的认识都取得了巨大进展。本文从射电、红外、可见光三个波段对激变变星的观测现象，如流量分布、光变曲线、驼峰现象和闪烁现象，以及对这些观测现象的理论解释作一简单介绍。

Multi-waveband Studies of Cataclysmic Variables(I)

Deng Shibing　Chen Jiansheng
(Beijing Astronomical Observatory, The Chinese Academy of Sciences, Beijing 100080)
Ma Jun
(Centre for Space Science and Applied Research, The Chinese Academy of Sciences, Beijing 100080)

Abstract

During the recent decade, our knowledge about the Cataclysmic Variables (CVs) has been greatly improved in both observation and theory. In this paper, we introduce some observational characteristics about Cataclysmic Variable at the radio, infrared and optical band, such as flux distribution, light curve, hump phenomenon and flickering. We also present some simple theoretical explanations of them.

1　Introduction

Cataclysmic Variables (CVs) are systems of interacting binary stars, in which the primary star is a white dwarf and the secondary star is a late type star imbued with its critical Roche lobe. Attracted by the primary star, the matter of the secondary star flows toward the primary star through the inner Lagrange point. Because of its intrinsic angular momentum, the matter forms an accretion circle around the white dwarf. Under the effect of viscosity the circle extends to a disk towards the surface of white dwarf. A

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great deal of gravitational energy is released in this accretion process, and contributes a luminosity of:

$$L_G = \frac{GM_{\rm wd}\dot{M}_{\rm acc}}{R_{\rm wd}} = 1.3 \times 10^{33}\dot{M}_{16}(\frac{M_{\rm wd}}{M_\odot})(\frac{10^9{\rm cm}}{R_{\rm wd}}){\rm erg}\cdot{\rm s}^{-1} \qquad (1)$$

where $\dot{M}_{16}$ is the accretion rate (in unit of $10^{16}{\rm g}\cdot{\rm s}^{-1}$).

According to the different light curves of CVs, we can classify them into three kinds, namely, nova, dwarf nova and nova- like star. The explosion of nova is caused by a nuclear burning on the surface of WD with explosive magnitude of about 7–20 mag, and we can divide them into fast novae and slow novae according to their different luminosity damping rates. Their explosive period is estimated at 10^4yrs to 10^6yrs. We will not discuss more about nova in this paper, because, on the one hand, it has a different explosive mechanism from other CVs, on the other hand there is a much detailed description about the multi- waveband observation and theory of novae in reference[2] . In comparison with nova, dwarf nova (DN) and nova-like star (NL) have a much smaller amplitude of light variation (<6mag). The former usually stays at a low luminosity state (quiescence), and occasionally enhances several magnitudes (outburst). On the contrary, NL is usually observed to stay at a high luminosity state, only occasionally found to become dim. According to the different light curves of DNe, they are divided into three sub-classes, i.e., U Gem stars, SU UMa stars and Z Cam stars. U Gem stars display only a normal outburst and SU UMa stars exhibit a brighter (about 1 mag) and much longer " superoutburst " in addition to the normal one, while for Z Cam type stars, there is a stage of standstill when they decline from the brightest point to the quiescence, during which the luminosity remains almost the same from several months up to several years. In the same way we can divide NL into three sub-classes according to the strength of their magnetic field of the primary stars. Of the first sub-class, including UX UMa stars and VY Sel stars, the magnetic field is too weak to destroy the accretion disk; the second sub-class, DQ Her stars, has a relatively strong magnetic field, which destroys the inner region of accretion disk; and of the third sub -class, AM Her stars, the magnetic field of WD is so strong that the accretion disk can not be formed. Distinguished from nova, luminosity variation of DN and NL is generally attributed to the instability of accretion rate. For detailed description about CVs, refer to [1–5].

2 Radio Radiation of CVs

The radio emission of CVs is relatively weak. VLA observation shows that[6,7] the radio radiation flux densities of most CVs are below the detecting limit (<1mJy). CVs with observed radio radiation are listed in Table 1. The estimated radio radiation scale of AM Her is about 10^{11} cm[8] . A distinguished flare of AM Her was observed, with a

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Tabel 1. Radio Observations of CVs.

Source	Type	Observing Frequency/GHz	Maximum Flux Density/mJy
SU UMa	SU	4.75	1.3
TY Psc	SU	2.5	10
U2 Boo	DN	2.5	2.4
AM Her	AM	14.85	0.5
		4.9	9.7
AE Aqr	DQ	14.85	18
		4.9	16
		1.4	5
V834 Cen	AM	8.4	2

Quoted from [9] and [36]

The high brightness temperature of AM Her indicates that its radio emission is originated from a nonthermal process. The radio radiation mechanisms of CVs mainly include synchrotron radiation and thermal bremsstrahlung. Perhaps the former is the main radiation mechanism in AM Her stars which have strong magnetic field, while for DN both radiation mechanisms are possible. The radio flare observed on AM Her may be caused either by the interaction and overlapping of the magnetic field of the primary star and the secondary star, or by the coherent process of plasma oscillation. Our knowledge about the radio emission of CVs is very limited, and further study is needed. For detailed description about CV's radio radiation mechanism, refer to [9].

3 Infrared Radiation of CVs

The infrared radiation of CVs mainly comes from secondary stars and accretion disks. Ritter's catalog showed [10] that most CVs' secondary stars have their mass $\leq 0.5M_{\odot}$, and so the secondary stars are mainly M-K type dwarfs, the radiations of which mostly concentrate in the infrared band and the red end of optical band. This argument is supported by observation. For example, Wade et al.[11] determined that the spectral type of the secondary star in Z Cha was M5.5V with respect to its spectrum in the 7000–9000Å region. Near infrared spectrum observation is a direct means to determine the spectral type of the secondary. Other examples of the determination of the spectral type of the secondaries include U Gem (M4–5V)[12], Z Cam(K7V)[13], etc.. For the spectral type of CVs' secondary stars, refer to [10] and [14].

Infrared radiation of accretion disk is mainly contributed by the outer disk . In a steady and optically thick disk, the temperature distribution is:

$$T_{\rm eff}(x)=T_{*}x^{-3/4}(1-x^{-1/2})^{1/4}, \qquad (2)$$

Where x is the distance to the center of WD, normalized by the radius of inner disk: $x=r/R_{\rm in}$, and

$$T_*=(\frac{3GM_{\rm wd}\dot{M}}{8\pi\sigma R_{\rm wd}^3})^{1/4}=4.1\times10^4(\frac{\dot{M}}{10^{16}{\rm g/s}})^{1/4}(\frac{M_{\rm wd}}{M_\odot})^{1/4}(\frac{R_{\rm in}}{10^9{\rm cm}})^{-3/4}{\rm K}. \qquad (3)$$

The effective temperature may be less than 5000K in the outer disk region. There are two proofs that the infrared radiation may come from the disk. First, the model disk spectra fit the observations very well[15]; second, variation of relatively long time scale was observed in the infrared band of some CVs, which can be ascribed to the effect of disk[16].

Now that both the disk and the secondary star contribute to the infrared radiation, which contributes more? The situation is quite different to individual CVs. Bailey considered that, for the short period CVs, both contributions are important, but for the long period CVs , only the contribution from the secondary star is essential [17]. On the contrary, Berriman et al. considered that the contribution of the disk can never be neglected in either case [16] . Sherrington and Jameson made an infrared observation to 22 CVs [18], and their results showed that, among 10 sources with obvious contribution from disk, only 2 cases can be simulated with $\nu^{1/3}$ disk spectrum [1], and 6 cases are found in a high brightness state. In the other 12 sources, the radiation from the secondary star is dominant. Generally speaking, the longer wavelength the radiation spectrum presents, the more the secondary stars contribute to the infrared radiation of CVs, while at K waveband, the radiation usually comes from the secondary star. Meanwhile, the ratio of the contribution from the secondary star to that from the disk is relatively larger in quiescence than in outburst. In addition, the inclination of the orbital system can also have some influences. The larger the angle of inclination, the smaller the contribution from the disk is.

As to the AM Her stars with a strong magnetic field, the accretion disk can not be formed. In this case, the infrared radiation mainly comes from the cyclotron radiation produced by the motion of electrons in the magnetic field during the column accretion process, and this will be discussed later in paper Ⅱ.

An important application of CV's infrared radiation is the estimation of the distance of the CVs. Define a K waveband surface brightness density [17]:

$$S_{\rm K}=K+5-5\log d+5\log(\frac{R}{R_\odot}), \qquad (4)$$

where K is the observed K magnitude, d is the distance, and R is the radius of the secondary star. Using an empirical formula, $S_{\rm K}$ can be calculated by colour index V−K[17], and $S_{\rm K}$ is approximately a constant for M and K dwarf. The radius of the secondary star can be calculated through Roche geometry[1,19]. Thus, by observing K and V–K, CV's distance can be approximately determined, which has a typical value of 100pc.

4 Optical Radiation of CVs

The usual definition phenomenon of CVs is referred to their violent quasi-periodic light variations in the optical band. The study of CVs through this window has the longest history and the deepest extent. Almost all the components of CVs– the primary star, the secondary star, the accretion disk, the hot spot and so on –have optical radiation, but usually most part of the optical radiation comes from the accretion disk.

4. 1 The proof that CV is a close binary

The direct proof that CV is a close binaries comes from the analysis of its light curve. As we do for other eclipsing binaries, we can determine its orbital period through the eclipse of the binary. Most CVs have a period between 80 min and 10h, corresponding to binary distance scale of 10^{11}cm, so they are close binaries.

First of all, what is the evidence for the existence of the secondary star? A direct evidence is that at a high speed photometry of VW Hyi during its quiescent state, the hump at the light curve is caused by the orbital motion of the secondary star [20]. Other evidences come from the spectral observation. The spectral lines of Z Cha display a periodic variation and present an "S" curve [11,12], which is caused by the Doppler effect of the secondary star's orbital movement. The orbital period can be determined from the phase of its velocity curve, and is just the same as the results from photometry. Now, what kind of star is the secondary? Theoretically, the secondary star fills its Roche lobe, and from the orbital period we can determine its average density $\bar{\rho} \approx 115\ p_{\mathrm{hr}}^{-2}\,\mathrm{g} \cdot \mathrm{cm}^{-3}$[1]. Then from the mass–radius relation of the main sequence star we can determine its mass, luminosity and so on. The results show that the secondary stars are mainly low mass dwarfs. All these conclusions depend on one presumption that : the secondary star is a

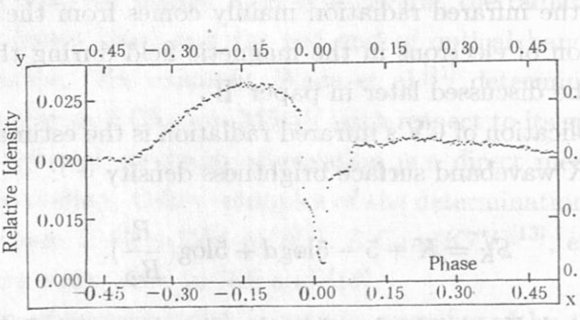

Fig.1 High speed photometry light curve of OY Car, where x coordinate is orbital phase, y coordinate is relative intensity [4].

main sequence star. How to confirm it or how to determine the secondary star's spectral type? The answer again comes from the observation. A typical example is BV Cen[21], which is a long period (P=14.68h)CV. There are many absorption lines in the spectrum after Doppler correction which is determined by the comparision with standard star spectrum , and it is found that its spectrum is most similar to G5-8V spectral type, a main sequence star spectral type. Similar situation is also found in V426 Oph[22], and its spectral type is K2–3V. The spectral type of the secondary stars indicates that they can be seen more clearly in the infrared wave band, and we have discussed this in the above section. Therefore, CV's secondary star should be a low mass dwarf in the main sequence state on the whole.

What is another component of the binary, i.e., the primary star? The first evidence again comes from photometry. Figure 1 is the light curve of OY Car [23], which has a very steep decadence of flux, and that is due to the eclipse of the primary star. From the eclipse we can determine that the eclipsed star's scale is about 10^9 cm, and from the spectrum observation we know that the primary star has a mass of about $1M_{\odot}$. The only object known with such mass and scale in today's astronomy is WD. Another example with the similar light curve is Z Cha[24]. Other evidences come from CV's short period light variation, such as AE Aqr which has an exact 33s periodic light variation. The variation is caused by the rotation of the primary star. Such a fast rotation indicates that the object is compact. When the non-disk AM Her star lies at a low luminosity state, the spectrum of WD can be seen at optical region directly. The absorption lines of WD's atmosphere are shown clearly by observations[25]. Because ordinary WD's effective temperature is above 10^4 K, some WD's atmospheric spectrum can be observed in the ultraviolet band. The most obvious example is WD's Ly α absorption (see the next section) . The compact primary star cannot be a neutron star, because the rate of CV's X ray flux to its optical flux is $L_X/L_{opt} \leq 1$, and we know the accretion system of a neutron star has a relation $L_X/L_{opt} \gg 1$[26].

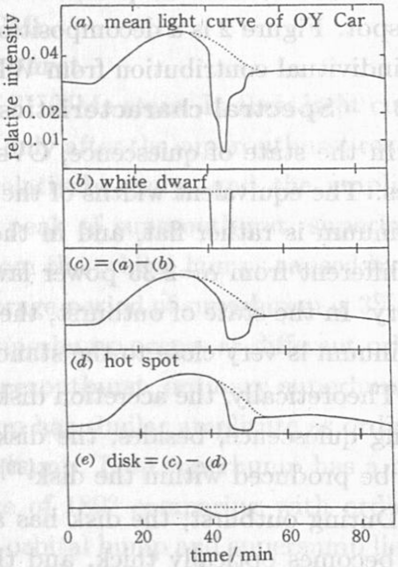

Fig.2　Decomposition of OY Car's light curve. (a) OY Car's average light curve in quiescence; (b)contribution from WD; (c)substract (b) from (a) ; (d) contribution from hot spot; and (e) contribution from the disk.

What is the evidence for the existence of accretion disk? In the CV's light curve (Figure 1), we notice that there is a rather wide eclipse, which shows the existence of a radiative object having a scale rather larger than WD. Some CVs have a clear "V" pattern eclipse, such as PG0810+513[27], and it is just a typical eclipse of a large extended disk. The rotation of the disk can also be seen in the spectral lines. Some highly inclined systems such as OY Car, Z Cha, etc., have a double peak configuration at their emission spectrum, in which both redshift and blueshift are observed. This shows that a part of emission matters move to us, and the others leave from us, which demonstrates an orbital rotation object. In combination with the eclipse, we can determine the center of the rotation. When the eclipse happens, one emission peak(blue) is eclipsed first, then the other peak (red), therefore the rotation center seems to be coincident with the location of primary star. The line wing is very broad, which could be due to the high speed rotation of the inner disk.

As a hot spot can be formed on the edge of the accretion disk hit by the accretion stream from the secondary star, is there any evidence from observation? On the OY Car light curve (Fig.1), apart from the eclipse, two parts are observed. One is a flat part, and the other is a hump. The hump comes from the contribution of hot spot at the edge of disk. It can only be observed in half the time, and in another half the time, it is invisible due to the blockage of the optical thick disk. In the analysis of OY Car's eclipse, except the WD's and disk's eclipses,we can see another component of eclipse, the eclipse from hot spot. Figure 2 is a decomposition of OY Car's eclipse, in which it can be seen clearly the indivitual contribution from WD, disk and hot spot [28].

4. 2 Spectral characteristics of CVs

In the state of quiescence, CVs exhibit an emisson line spectrum, such as balmer series. The equivalent widths of the lines are commonly in the range of 10–100 Å[29]. Its continuum is rather flat, and in the power law of $f_\lambda \propto \lambda^{-\alpha}$, we have $\alpha < 2$, which is far different from α=2.33 power law spectrum predicted by a steady optical thick disk theory. In the state of outburst, the spectrum is dominated by absorption lines, and the continuum is very close to the standard 2.33 power law spectrum.

Theoretically, the accretion disk of CVs has a very low accretion rate ($\leq 10^{16}\mathrm{g}\cdot\mathrm{s}^{-1}$) during quiescence, besides, the disk may be optically thin, and the emission line of H may be produced within the disk[30].

During outburst, the disk has a much higher accretion rate ($\sim 10^{17} - 10^{18}\mathrm{g}\cdot\mathrm{s}^{-1}$), and becomes optically thick, and the radiation of the disk is just like the radiation of a star's atmosphere [31–33]. In the paper Ⅱ we will continue our discussion about the CV's spectral feature (ultroviolet).

4. 3 Magnetic CVs

Magnetic CVs include DQ Her stars(with a weak magnetic field) and AM Her stars (with a strong magnetic field). The inner disk of DQ Her stars is destroyed by the magnetic field , and in AM Her stars, the entire disk is destroyed[3]. So they have many

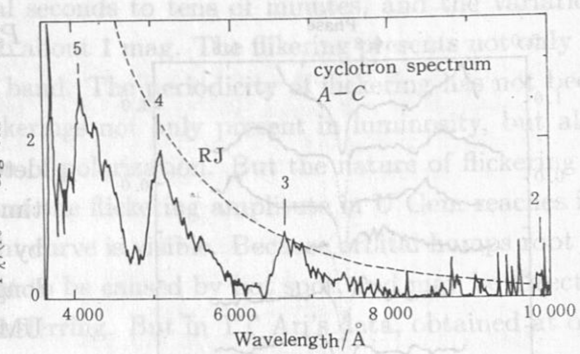

Fig. 3. Cyclotron spectrum of UZ Ser. The digits on the map indicate the number of harmonic. RJ is the Raleigh-Jeans spectrum with regard to the third harmonic[4].

distinctive observational characteristics from the non-magnetic CVs. The first characteristic is the cyclotron spectrum, because strong magnetic field(20–60MG) makes the cyclotron radiation observable in the infrared and optical range. The basic frequency of cyclotron radiation is $\nu_{\rm cyc} = eB/2\pi m_{\rm e}c = 2.8\times10^{13}$ $(B/10^7\mathrm{G})$ Hz, and if B=30MG, the corresponding basic frequency falls on 3.6μm, which is exactly in the infrared range. Figure 3 shows such an example (UZ Ser)[34]. The second characteristic is the polarization of the radiation. AM Her type star has strong linearly and circularly polarized radiation[35]. Zeeman effect is another observational characteristic of AM Her stars. These characteristics are caused by magnetic field, so they are also used as a basis of the measurement of the magnetic field of CVs. Because of the relatively weak magnetic field in the DQ Her star, no evidence of magnetic field has been found except in the BG CMi.

4. 4 Superhump phenomenon in the superoutburst

Superhump appears only in the superoutburst of SU UMa stars. In their light curves superhump presents as a periodic hump, and appears only after the superoutburst reaches its maximum. At its early stage, superhump is relatively sharp, and the amplitute is about 30%–40%. During the declining from the peak of superoutburst, superhump decreases and broadens correspondingly. Different from the orbital humps caused by hot spot (they are very steady at the phase of orbit) , average period of superhump is 3%–7% longer than the orbital period, therefore each time superhump occurs at different orbital phase, as shown in Figure 4. With the decline of superoutburst, ordinary superhump is replaced by a " late superhump ". Late superhump has similar amplitute as ordinary orbital hump, but its period is close to that of superhump. Late superhump has a most peculiar characteristic that it has a phase difference of 180° comparing with ordinary superhump[37]. Furthermore, the differences between orbital hump and supersump lie not just in their period. Occurring only at quiescence or the late time of the decline from the outburst, the orbital humps are not observed at the outburst (including superoutburst), and they present only at high inclination (eclipse) systems; while the superhumps appear only at superoutburst and have nothing to do with inclinations. For detailed description of superhump, see reference [38].

There is an empirical relation between the superhump period and orbital one[39]:

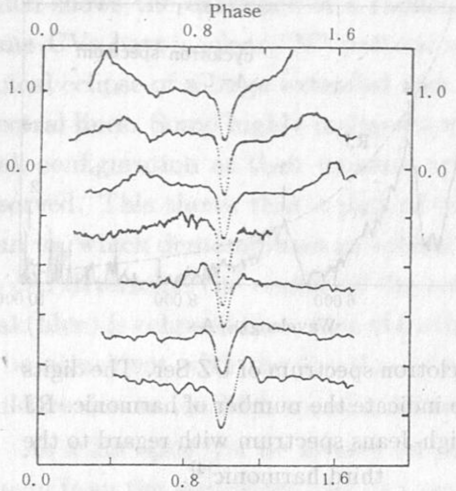

Fig. 4. Superhumps in the superoutburst of Z Cha. In the uppermost curve, the maximum superhump appears at phase 0.35, and it shifts backward gradually. In the lowest curve, the superhump appears at phase 0.1. Data came from the observation of different superoutburst[1].

$$\frac{P_{\mathrm{s}}-P_{\mathrm{orb}}}{P_{\mathrm{orb}}}=-3.3\times10^{-3}+0.84P_{\mathrm{s}}(\mathrm{d}) \quad (5)$$

Therefore, the orbital period can be determined from superhump period. Sometimes we directly draw out orbital period by assuming that superhump period is 3% longer than the orbital period, such as SS UMi[40]. Many orbital periods listed in Ritter's catalog[10] were determined by this empirical method.

There are many models about superhump. The most successful one is based on tidal interaction, obtained by means of numerical simulation[41–43]. The simulation showed, when the mass ratio $q = M_{\mathrm{sec}}/M_{\mathrm{pri}} \leq 0.25$–$0.33$, the accretion disk took shape of a ellipse under the tidal effect of the secondary star, and made precession along the orbital direction. The precession period is a little longer than the orbital one. The precession produces shear and dissipation, and directly results in light modulation with the same period, i. e. superhump. Basically speaking, superhump is a resonance between the motion of particles in disk and that of secondary star relative to the particles[1,44], and the period of superhump can be expressed as follows:

$$P_{\mathrm{s}}=\frac{6\pi}{\Omega}\approx P_{\mathrm{orb}}(1+2\omega/3\Omega_{\mathrm{orb}}), \quad (6)$$

Where Ω is the average angular frequency of particles rotating around primary star, and ω is apsidal precession frequency, $\omega \ll \Omega_{\mathrm{orb}}$. Detailed description is in [44] and [1].

It is generally considered that late superhumps are unlikely caused by tidal effect. One opinion was that it may result from modulation between the gravitational potential variation of hot spot and the orbital movement[45]. Hessman's recent work[46] didn't back up this point of view. He considered that superhump may come from modulation of outer disk surface density, while such elliptically induced modulation can produce the similar light variation as hot spot. However,it has a different mechanism against hot spot.

4. 5 Flickering

In almost all CVs, a short period light variation called " flickering " is observed.

The variation time scale is from several seconds to tens of minutes, and the variation amplitude is from several percent mag to about 1 mag. The flikering presents not only in the optical band, but also in the X-ray band. The periodicity of flickering has not been found . As to AM Her stars, their flickerings not only present in luminosity, but also demonstrate a short time scale variation of polarization. But the nature of flickering is not clear yet. Warner et al.[48] found that the flickering amplitute in U Gem reaches its maximum value, when orbital hump light curve is visible. Because orbital humps root in hot spot, the flickering was once thought to be caused by hot spot, and may be directly come from the instability of matter transferring. But in TT Ari's data, obtained at optical and X-ray bands simultaneously, flickerings in both of the two bands were found. Because hard X-ray ($kT > 2$keV) can not be produced at outer disk, it means that flickering may come from the region near WD[49]. Furthermore, in the observation of HT Cas, flickering was found at its maximum amplitude when the hot spot was eclipsed[50], and it indicates that flickering cannot come from hot spot at least in HT Cas. Similar cases are also found in V2051 Oph[51], RW Tri[52], OY Car[53], etc. Studies of these CVs show that flickering may come from the region near WD. Recently, Bruch [54] make a systematic study of CV's flicking phenomenon. He analysed possible mechanisms of flickering, and agreed with the argument that flickering comes from inner region, and it may be caused by the turbulent flow of inner disk or the instable process of accreting matter to WD. He also argued considered that the mechanism may not be unique. In AM Her star which has no accretion disk, flickering may be caused by relatively dense blob in accretion stream. The irregular blob may be produced at inner Lagrange point or by interaction between accretion flow and magnetic field[35].

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