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THE GENERAL TRENDS OF RECURRENT NOVAE

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Abstract.
The observational properties of recurrent novae are reviewed in this talk. The class of recurrent novae may be divided into subgroups as (a) systems with a dwarf secondary and (b) systems with a giant secondary. The primary in these systems is a white dwarf, accreting at rates $\sim 10^{-8}$ $M_\odot$ yr^{-1}. The outbursts are powered by thermonuclear runaway reactions on the surface of the white dwarf.

1. Introduction

Recurrent novae (RNe) constitute a small class of objects which bear many similarities to the classical novae. These systems undergo outbursts with a recurrence period of $\sim 8-80$ years. Webbink et al (1987) proposed that the designation of RNe be restricted to those systems which have two or more recorded outbursts (a) reaching an absolute magnitude comparable to those of classical novae ($M_V \leq -5.5$) and (b) accompanied by the ejection of a high velocity shell with $V_{\rm exp} \gtrsim 300$ km s^{-1}. The first criterion distinguishes RNe from dwarf novae, while the second distinguishes them from symbiotic novae. Till date, there are eight systems known which satisfy the above criteria — TPyx, USco, V394CrA, Nova LMC 1990#2 (LMC#2), RSOph, TCrB, V3890Sgr and V745Sco.

The observational properties of these systems, both at quiescence and at outburst indicate heterogeneity of the group. The infrared colours of these systems at quiescence (Harrison et al 1993) clearly indicate they may be further sub-classified as (a) systems with dwarf secondary — TPyx, USco, V394CrA, LMC#2 and (b) systems with giant secondary — RSOph, TCrB, V3890Sgr, V745Sco.

The outbursts in RNe are powered by thermonuclear runaway (TNR) reactions on white dwarfs, similar to classical novae. For the recurrence of the outbursts to be of the order of a few decades as observed, the models require a massive white dwarf ($M_{\rm WD} \gtrsim 1.3\ M_\odot$) accreting at rates $\dot{M}_{\rm acc} \gtrsim 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ (Starrfield et al 1985). Prialnik and coworkers (these proceedings) have however been able to reproduce recurrent nova outbursts on white dwarfs not necessarily massive. Webbink et al (1987) and Livio (1988) proposed an alternative outburst mechanism for RSOph and TCrB, i.e. systems with a giant secondary. According to their model, the outbursts are powered by accretion events by a burst of mass transfer from the giant secondary onto the primary, which is a main-sequence star. However, recent outbursts of RSOph, V3890Sgr and V745Sco show no evidence for the presence of a main sequence accretor. Further, Kato (1991) has successfully been able to model the outbursts of RSOph as TNR events.

In what follows, the observational properties of these systems will be discussed. Also, the observational evidences which indicate a TNR powered outburst in the systems with giant secondary will be discussed.

2. Systems with Dwarf Secondary

This class has four members; TPyx, USco, V394CrA, LMC#2. Of these four, except TPyx, the other three members are similar in their observational properties.

2.1. T PYXIDIS

TPyx is distinctly different from the other members of the class of recurrent novae, both during outburst and at quiescence. At outburst, this nova has an extremely slow development of the light curve with a rate of decline 0.034 mag day^{-1}. The spectral development (Catchpole 1969) during outburst is similar to classical novae, with the development of absorption systems. The broad band $B-V$ and $U-B$ colors become redder during rise to visual maximum, characteristic of an expanding photosphere, as in the case of classical novae. The outburst development is remarkably similar during each outburst.

At quiescence, TPyx has a typical disk spectrum. The broad band colors are extremely blue $(B-V)_0 = -0.26$, $(U-B)_0 = -1.25$ and $(V-R)_0 = -0.11$, indicating a high mass transfer rate ($\dot{M} \sim 5 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$) on a short period system. The UV continuum energy distribution is remarkably constant in slope and intensity, while the emission lines show substantial changes in their intensity (see Selvelli et al, these proceedings).

The spectral and light curve development during outburst, and the colors during quiescence indicate the outbursts are powered by TNR reactions on the white dwarf, accreting at a high rate. Starrfield et al (1988) and Kato (1990) have modeled the outbursts of TPyx. Kato also gives a prediction of the light curve energetics for the next outburst.

Photometry during the years 1966–1990 (Shaefer et al 1992) indicates a roughly sinusoidal modulation ($\Delta m = 0.09$ mag). The orbital period varies between 2.5–1.5 hrs with the best estimate for the period as 0.07616 ± 0.00017 days (1.82784 ± 0.00408 hrs). The sinusoidal motion does not appear tied with the orbital period. Vogt et al (1990) obtain a spectroscopic period $P = 3.439$ hrs, with $K = 30$ km s^{-1}, a mass function $f(m) = 0.00028\ M_{\odot}$, and $i = 27°$.

TPyx is unique among recurrent novae in having a discernable nebulosity around it. This nebulosity consists of an inner shell ~ 10 arcsec in diameter, with a faint diffuse envelope almost 20 arcsec in diameter surrounding the inner shell (Duerbeck & Seitter 1979, Williams 1982, Shara et al 1989). These shells are formed by the outflowing gas from previous eruptions. The shell is clumpy in nature similar to the shell of GK Per (Shara; these proceedings). The distribution of nitrogen in the shell is asymmetric while the distribution of oxygen is symmetric (Anupama 1990). The shell is a slowly expanding ($V_{\rm exp} = 350$ km s^{-1}), photoionised gas with roughly solar abundances (Shara et al 1989, Williams 1982).

2.2. U SCORPII ET AL

This class of recurrent novae have an extremely fast development of the outburst. The light curve declines at a rate ~ 0.6 mag day^{-1}. The outburst is accompanied by the ejection of matter at extremely high initial velocities. No absorption systems are present in the outburst spectrum. The emission lines are extremely broad (FWZI $\sim$ 10000 km s^{-1}). He II lines are extremely strong, and the helium abundance He/H~ 2 indicate helium enhancement. Nitrogen is enhanced compared to carbon and oxygen, while the CNO abundance is nearly solar. This indicates a TNR processing. The outburst luminosity is super Eddington. The continuum spectrum during the later stages of outburst is extremely flat, with $S_{\nu} \propto \nu^{0.4}$. The outburst characteristics are similar at each outburst.

The spectrum at quiescence is unusual in the absence of hydrogen lines, and the presence of strong helium lines. The absence of hydrogen lines indicate an under abundance of hydrogen (Duerbeck et al 1993, Johnston & Kulkarni 1992, Duerbeck & Seitter 1990). The secondary is of spectral type F8–G6 in U Sco (Johnston & Kulkarni 1992, Schaefer 1990), and of type G (later than USco) in V394CrA (Duerbeck et al 1993).

Photometry of U Sco (Schaefer 1990) show eclipses with an amplitude of ~ 1.5 mag. The duration of the eclipses is 0.17 in phase with flickering outside the eclipses. The estimated period is $P = 1.2344 \pm 0.0025$ days. V394CrA also shows a large and significant variablity in its quiescence magnitude (Schaefer 1990), which are roughly sinusoidal with a period $P = 0.7577$ days.

USco is an ideal test for TNR models of RNe since both radial velocity curves, that of the white dwarf and the cool component can be measured. Further, masses of the individual components can also be estimated. Johnston & Kulkarni (1992) estimate the following parameters: secondary spectral type F8±2, $P = 1.225806$ day, $K_{WD} = 35 \pm 17$ km s^{-1}, $K_s = 156 \pm 19$ km s^{-1}, $f_a(M_{WD} = 0.0054\ M_\odot$, and $M_{WD} = 0.23 \pm 0.12\ M_\odot$for $M_s = 1.3\ M_\odot$. They obtain a 3σ limit to the mass of the white dwarf as $M_{WD} = 0.9\ M_\odot$. This poses a problem for the TNR powered models of outburst, which require a massive white dwarf.

Duerbeck et al (1993) have remeasured the radial velocities for USco, and obtain the following parameters: $P = 1.234518$ day with a sine fit scatter of 74 km s^{-1}, $K_{WD} = 164 \pm 333$ km s^{-1}, $K_s = 116 \pm 35$ km s^{-1}, $M_s = 1.64 \pm 0.83\ M_\odot$, and $M_{WD} = 1.16 \pm 0.69\ M_\odot$. This estimate of the mass of the white dwarf is compatible with TNR models. It should be noted here that both USco and V394CrA are extremely faint at quiescence, and the data on which the radial velocity measurements are based are fairly noisy with large uncertainities. Better quality data are required for an accurate estimate of the binary parameters.

3. Systems with Giant Secondary

This class consists of four members, RSOph, TCrB, V3890Sgr and V745Sco. These four systems are quite similar in their properties. They are fast novae with a rate of decline ~ 0.3 mag day^{-1}. Matter during outburst is ejected with extremely high initial velocities (~ 4000 km s^{-1}), which decrease with time. Also, the spectrum develops high excitation coronal lines and OI 8446 Å line enhanced by Lyβ fluorescence (see for eg. Williams et al 1991). RSOph was detected as a strong X-ray source about 55 days following the 1985 outburst maximum, and also as a synchrotron emission source in the radio at a similar period (Mason et al 1987, Hjellming et al 1986). The development of the strong coronal lines, the narrowing of the emission lines and the development of non-thermal X-ray and radio radiation in these systems is interpreted as arising from a region shock heated as the fast moving nova shell interacts with the slow moving pre-outburst circumstellar material from the stellar wind of the giant companion (Gorbatskii 1972, Bode & Kahn 1985, O'Brien & Kahn 1987, O'Brien, Bode & Kahn 1992).

The optical spectrum at quiescence is composite, with strong emission lines superposed over the spectrum of the late type giant secondary, similar to the symbiotic stars. The origin of the emission lines is uncertain. The spectral type estimate for the giant secondary is:

T CrB: M3
RS Oph: K5–M1
V745 Sco: M4–M7
V3890 Sgr: M5–M8

In the next two sections, the systems TCrB and RSOph at quiescence are discussed in detail.

3.1. T CRB

At quiescence, TCrB is the brightest recurrent nova $V \approx 10.2$ mag. Sanford (1949) first detected radial velocity variations with a period of 230.5 days and velocity amplitude $K_g = 21$ km s^{-1}. The orbit was later refined by Kraft (1958), by Paczyński (1965) and most recently by Kenyon & Garcia (1986). The orbital parameters as estimated by Kenyon & Garcia are: $P =$ 227.53 days, $K_g = 23.32$ km s^{-1}, $K_h = 33.76$ km s^{-1}, $i \approx 68°$, $M_g =$ $3.34 \pm 0.73\ M_{\odot}$, $M_h = 2.31 \pm 0.29\ M_{\odot}$.

The mass estimate for the hot component implies a main sequence accretor, and poses a problem for TNR powered outburst models. Webbink (1976) proposed an accretion powered outburst model, with sporadic mass transfer onto the main sequence accretor. It should be noted here that the origin of the emission lines is uncertain, and is probably not associated with the hot component. In this case, the velocity amplitude K_h which is based on the emission lines does not represent the hot component, and hence the estimated mass cannot be attributed to the hot component.

The optical quiescence spectrum is dominated by that of the giant secondary, while the UV spectrum is that of an accretion disk. Selvelli et al (1992) describe the UV spectrum in detail and from their estimates of the UV luminosity and mass accretion rates give arguments for the presence of a white dwarf accretor. The slope and luminosity of the UV continuum energy distribution is found have variations. The mean UV luminosity of $\sim 40\ L_{\odot}$ implies a mean transfer rate of $\sim 5 \times 10^{-8}\ M_{\odot}$ yr^{-1}. Similar rates are implied by the HeII 1640 Å luminosity. The EUV luminosity estimated based on the HeII line flux, implies an inner disk temperature $T_* = 3 \times 10^5$ K.

The emission line strengths in the UV region are variable and correlated with the UV continuum variations. Variability is also present in the optical emission lines. Hα emission line shows a long term variation with orbital phase dependant variations superposed (Anupama & Prabhu 1991). Maxima in intensity occurs around phases 0 and 0.5, which is anti-correlated with broad band photometric variations, which show a minima around these phases (Peel 1990), but correlated with UV variations. These variations probably arise due to a variation in the mass transfer rate.

3.2. RS OPH

The 1985 outburst of RSOph was extremely well studied in all wavelength regions, from the X-rays to radio, the details of which may be obtained from Bode (1989).

At quiescence, this star resides at $m_{\rm vis} \approx 11.5$ mag, with variations of the order $\Delta m \sim 0.5$ mag. Oppenheimer & Mattei (1994) analyzed the visual magnitudes of RSOph from 1930–1993 in the AAVSO archives. They find several significant periods in each interval between outbursts. No single period repeated from one interval to the next. Analysis of a similar data by Dobrzycka & Kenyon (1994) show the light curve to be a superposition of a long period variation (2178 ± 160 days) and a short period variation (508 ± 46 days). Analysis of visual magnitude estimates between 1979–1994 (Anupama & Gilmozzi 1994) reveals periods of $P \sim 1500$ days and $P \sim 470$ days.

Garcia (1986) obtained the orbital parameters for this star, which has recently been revised by Dobrzycka & Kenyon (1994) as: $P = 460 \pm 10$ days, $K_{\rm g} = 12.8 \pm 2.0$ km s^{-1}, $K_{\rm h} = 4.6 \pm 1.4$ km s^{-1}, $i \lesssim 40°$. As in the case of TCrB, the origin of the emission lines and hence the value of $K_{\rm h}$ is uncertain. Dobrzycka & Kenyon treat RSOph as a single lined spectroscopic binary, and assuming $M_{\rm h} \sim 1.4\ M_{\odot}$, they obtain $M_{\rm g} \lesssim 1.4\ M_{\odot}$. The spectroscopic period is similar to the short period detected in photometric data.

Similar to TCrB, RSOph also shows variations in the UV (1150–3000 Å) continuum slope and intensity (Anupama & Gilmozzi 1994). The variations appear correlated with the visual magnitude variations. For eg. the UV luminosity reached a maximum in 1982 October, when the visual magnitude also recorded an increase to 9.2 mag. The mean UV luminosity of $L_{\rm UV} \sim 10^{36}$ erg s^{-1} implies a mass transfer rate of $\dot{M} \sim 6 \times 10^{-8}\ M_{\odot}$ yr^{-1}. The He II 1640 Å flux also implies a similar mass transfer rate. The inner disk temperature is $T_{*} \sim 7 \times 10^{5}$ K. Corresponding to this temperature, the outer radius of the optically thick disk is $R_{\rm out} \sim 1\ R_{\odot}$. The presence of a large accretion disk is consistent with the extremely blue continuum in the optical region.

The optical spectrum is a combination of an extremely blue continuum superposed over which are strong emission lines of the hydrogen Balmer series, FeII, HeI, CaII and OI 8446 Å, and that of the giant secondary. The presence of the TiO bands indicate a spectral type K5–M1 for the secondary. The CaII and FeII emission lines originate in a region with $n_e \sim 10^{12}$ cm^{-3}

and $T_e \sim 6000 - 7000$ K (Anupama & Gilmozzi 1994), possibly in the stellar wind photoionized by the hot white dwarf.

The hydrogen lines show a variable broad component which is double peaked either in the blue or red side of the narrow component (Iijima et al 1994). Variations have also been detected in the secondary spectral type, from K5–M2 (Anupama & Gilmozzi 1994), and these are possibly correlated with the variations in the UV flux and the visual magnitudes.

RSOph has also been detected as a soft X-ray source at quiescence by ROSAT (Orio 1993). Assuming an optically thin model of thermal plasma, Orio obtains an X-ray luminosity of $L_X \simeq 2.8 \times 10^{31} - 1.64 \times 10^{32}$ erg s^{-1}. This implies a mass transfer rate $\dot{M} < 10^{-9}\ M_\odot$ yr^{-1}, a value much less that that estimated by UV data.

3.3. NATURE OF THE HOT COMPONENT

There are no observational evidences for the presence of a main sequence accretor from the recent outbursts of RSOph (1985), V745Sco (1989) and V3890Sgr (1990). We present in this section the evidences for the presence of a white dwarf accretor.

RSOph 1985 outburst

- Detection of remnant X-ray radiation 250 days after outburst maximum, implying a temperature $T = 3.5 \times 10^5$ K, luminosity $L = 10^{37}$ erg s^{-1} and a blackbody radius $R \sim 10^9$ cm.
- Radius and temperature of the central ionizing source inferred from hydrogen and helium emission lines, 204 days after outburst maximum (Anupama & Prabhu 1989): $T_* = 3.6 \times 10^5$ K, $R_* = 0.03\ R_\odot$.

V3890Sgr 1990 outburst

- Radius and temperature of the central ionizing source infrerred from hydrogen and helium emission lines, 18 days after outburst maximum (Anupama & Sethi 1994): $T_* = 3 \times 10^5$ K, $R_* = 0.06\ R_\odot$.

TCrB at quiescence

- Bulk of the disk luminosity arises in the UV with negligible contribution in the optical. The observed UV luminosity ($\sim 40\ L_\odot$) is incompatible with a main sequence accretor as this would imply extremely high accretion rates ($\sim 10^{-3}\ M_\odot$ yr^{-1}) and hence significant contribution in the optical region, which is not observed (Selvelli et al 1992).
- Presence of strong HeII 1640 Å line, implying temperatures $\sim 10^5$ K (Selvelli et al 1992).
- Presence of broad wings (velocities ~few 100 km s^{-1}) in the emission lines of CIV and HeII (Selvelli et al 1992).
- Flickering in U band photometry (Walker 1977).

OI 8446 line

• Presence of strong OI 8446 Å line in the quiescent spectrum of RSOph and V745Sco. This line which is enhanced by Lyβ fluorescence indicates the presence of a hot source of UV photons.

3.4. OUTBURST PROCESS

Observational evidences exist for the outbursts in these systems to be powered by TNR reactions on the surface of the white dwarf. We list here the evidences.

RSOph

• Sustained bolometric luminosity plateau lasting over 57 days from outburst (Snijders 1987, Evans et al 1988).

• Increase in temperature of the ionizing source with a decrease in the radius with increasing time, following the 1985 outburst maximum (Anupama & Prabhu 1989).

• Outburst luminosity of $1.3 \times 10^5\ L_\odot$(Harrison et al 1993).

• Elemental abundances indicating enhancement of helium and nitrogen (Snijders 1987, Bohigas et al 1989, Anupama & Prabhu 1989).

V3890Sgr

• UV maximum was reached $\sim$ 20 days after visual maximum, similar to what happens in classical novae (Gonzalez-Riestra 1992).

• Estimated IUE luminosity 18 days after the outburst: $L_{\rm UV} = 1.3\times 10^5\ L_\odot$, implying $L_{\rm bol} >> L_{\rm Edd}$ (Gonzalez-Riestra 1993).

• An enhanced helium abundance of He/H= 0.2 (Anupama & Sethi 1994).

Mass accretion rates

• The mass accretion rates estimated from the UV luminosity for both TCrB and RSOph at quiescence, which have values $\gtrsim 10^{-8}\ M_\odot\ {\rm yr}^{-1}$.

4. Conclusions

In conclusion, the class of recurrent novae may be divided into two different subclasses based on the nature of the secondary: (a) systems with dwarf secondary and (b) systems with giant secondary. The first subclass is further ditinguished as the USco type or the TPyx type. The outbursts in recurrent novae are powered by TNR reactions on the white dwarf accreting at rates $\sim 10^{-8}\ M_\odot\ {\rm yr}^{-1}$.

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