Chapter 1

Introduction

1.1 Introduction to the Cataclysmic Variable Stars

Though there are thousands of billions of stars in heaven most of them do not show any kind of observable variability in time scale of human life. Possibly one in a thousand stars appears variable with time scale of tens of years or less. Cataclysmic Variable stars belong to one such class of variable stars.

According to the Cambridge dictionary “cataclysm” means "A large scale and violent event in the natural world". This is very true for the cataclysmic event - The sudden large scale brightening leading to the outburst seen in Cataclysmic Variables. Cataclysmic Variable stars (CVs) show a large variety of variability such as changes in brightness, spectra and polarization at all wavelengths from X-rays to radio waves at time scale ranging from few tens of seconds to few tens of years and also the brightness varies from a few tens of milli-magnitudes to a few magnitudes. This is the reason why CVs is a subject of interest for professional as well as amateur astronomers.

There are several subclasses of CVs known, broadly divided into four subclasses, namely Nova, Dwarf Nova, Nova like and magnetic CV. Nova is the subclass that shows highest change ($\Delta m \sim 8$magnitude) in brightness among CVs seen as nova outburst. Dwarf novae are the next to novae showing sudden brightness
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(Δm ~ 5 magnitude) with a sudden bright increase. Nova likes mainly comprises of CVs that do not show bright outburst but show brightness variation at smaller timescales. Magnetic CVs comprises a relatively strong \((B > 1MG)\) magnetic white dwarf and hence strong interaction of plasma with magnetic field is seen. This classification is quite broad and each subclass is further subdivided.

Novae have been known for many centuries. Numerous observations of temporary objects have been recorded in Astronomical records maintained by Chinese, Japanese and Korean astronomers since 1500 BC. Among these some objects may be novae and supernovae (Clark and Stephenson, 1976, 1977). In post Copernican era, it is surprising that only one true nova (Nova Vulpecula 1670) was discovered, No nova was discovered in whole eighteenth century and only one nova (Nova Ophuichi 1848) was discovered in the first half of the nineteenth century. Active participation of amateur astronomers and the introduction of photographic techniques increased this number dramatically. Although it was only in the early decades of the 20th century that novae were first clearly distinguished from the even more powerful supernovae.

Dwarf novae were discovered much more recently and quite gradually, with U Geminorum being the first seen in outburst in 1855 by J.R. Hind (Hind, 1856) and the second one, SS Cygni, was discovered by Miss Louisa D. Wells in 1896. Subsequently, many more dwarf novae (abbreviated to DN) have been discovered and studied. There are three distinct subtypes of DN, based on the morphology of the outburst light curves. U Gem, SU UMa and Z Cam are the prototype stars of three major subclasses of DN.

With the introduction of photomultipliers in 1940s, various properties of light curves of CVs, like presence of flickering, peculiar shapes of eclipses, very fast and periodic modulations were discovered. This in turn helped understanding the common underlying structure of CVs.

Spectroscopic observation by Joy (1940) revealed that at minimum light the spectrum of dwarf nova RU Peg is composite of an absorption spectrum an an
emission line spectrum which suggested the binary nature of the star. His further work along with the discovery that DQ Her is an eclipsing binary (Wallace, 1954) led to the speculation that the all CVs might be binary systems (Kraft, 1962). Eventually, in 1960s Robert Kraft and colleagues first time confirmed for the first time the initial suspicion that cvs are close binary systems where the mass transfer occurs leading to the outburst.

1.2 Structure of CVs

Figure 1.1 shows the general structure of the non-magnetic CV which comprises of a compact white dwarf primary star and a red dwarf secondary star orbiting in close binary system. Accreting mass from secondary to Primary forms a disc around White dwarf and also a bright spot is produced at the site of interaction of accretion stream with disc. Figure 1.2 shows the contours of equal gravitational potential drawn for a binary. The dark solid line shows the Roche-lobe of primary and secondary stars. Inner Lagrangian point L1 is also shown. Figure 1.2 also shows the visualization of Roche lobes as gravitational wells. The transfer of mass from secondary to primary can be visualized.

Since the white dwarf radius is too small compared to the binary separation, it remains spherical. But the less dense secondary fills its Roche-lobe and hence distorts significantly from the spherical shape. Some of the material of secondary star leaves its Roche lobe and enters in the Roche-lobe of the primary. This accreted material moves under primary’s gravitational attraction. However, the material leaves L1 has angular momentum due to orbital motion. This conservation of angular momentum do not allow material to fall on to the primary but to form a ring as shown in Figure 1.3. Eventually, this ring extends towards the white dwarf to form a disc because of the viscous interaction in the ring.
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Figure 1.1 Schematic diagram of a non-magnetic Cataclysmic Variable Star. Various components are shown in the figure.

Figure 1.2 Structure of Roche-Potential of binary system is shown here. The 3-dimensional net shows the change of potential at different point in the orbital plane of binary system. Vertical axis is potential increasing upward. Horizontal plane is binary orbital plane. Lower diagram is cross-section of boundaries of equipotential surfaces with orbital plane.
Figure 1.3  Schematic diagram of various stages of disc formation from beginning of mass transfer.
1.2.1 Primary Star

The primary stars of all CVs are assumed to be White Dwarfs. This makes the CVs semi-detached binary star system. Since the temperatures of the primaries in CVs are tens of thousands of Kelvin, they are expected to radiate essentially in the UV, but they can be visible also in the optical range if they are not too hot. However, the geometrical dimensions of the white dwarfs are negligible compared to those of the accretion discs and hot spot and hence white dwarf is outshone by these components. Therefore direct observations of white dwarf is possible only when they belong to high inclination system or when they accrete matter with a very low mass transfer rate.

Precise measurement of Temperatures of white dwarfs are possible only in few cases. This can be done either from white dwarf spectra or by modelling primary’s eclipse in different bands (e.g., Wood et al. (1986)). Temperatures of primaries range between 10000 K and 100000 K. It has also been noted that the WDs in CVs above the period gap are hotter and more accretion heated than those below the gap Urban and Sion (2006).

1.2.2 Secondary Star

The secondary stars are usually cool main sequence stars. However in some cases they are evolved stars also. MK spectral type of the secondaries can be obtained from their spectral features like NaI and TiO bands in the spectrum. Spectral type ranges from G8 to M6, corresponding to temperature from 5000 to 3000 K. Therefore, secondaries contribute substantially to the integrated radiation only in the red and infra-red part of the spectrum. However, spectral feature strengths change around the orbit, due to irradiative heating of the secondary star. Therefore it is expected that the spectral type of the secondaries are likely to be earlier compared to isolated star. Empirical relationship has been developed between orbital period of the system and spectral type of the secondary star (Knigge, 2006)
Figure 1.4 Modulation of infrared light with orbital period. The modulation at first harmonic of orbital period is explained by varying aspect of secondary star during its orbital motion.

which is discussed in more detail in section 1.5.

Assuming that the secondary star is main contributor in IR light of CV it is possible to infer the distance of the system if spectral type of the secondary is known. Moreover, since secondary star is Roche-lobe filled it is no more spherical. The projection of distorted shape of secondary varies twice in the orbital period. This produce ellipsoidal variation in IR light curves. By modeling this variation one can estimate the inclination of the system.

1.2.3 Roche-Lobe Geometry and Accretion Stream

If two stars are too close to each other, tidal interactions other than simple inverse square law gravitational attraction between point masses takes place. These tidal interactions combined with centrifugal effects distort both components. Such binary system is known as Close binary system. In the case of CV, The secondary star is always largely distorted through the gravitational influence of the white dwarf primary star, but the white dwarf unaffected from tidal forces due to its small radius. Moreover, these tidal forces synchronize the secondary star rotation
with orbital motion and also eliminates any initial eccentricity of orbit in very short timescale compared to the life time of a CV. Therefore, all CVs have circular orbit with period $P$ can be determined by Kepler's second law

$$P_{\text{orb}}^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)} \tag{1.1}$$

Where $a$ is the separation between the centers of mass of the binary components and $M_1$ and $M_2$ are the masses of the primary and secondary respectively.

In order to calculate the distorted shape of the secondary let us take a cartesian coordinates $(x,y,z)$ with origin at the primary star, where the $x$-axis lies along the line of centers, the $z$ axis is perpendicular to the orbital plane and the $y$-axis is in the direction of orbital motion of the primary. Moreover, this coordinate system rotates with the binary. We also assume that the mass of each star is concentrated at the center of the star. With these assumptions the total potential at any point, which is the sum of the gravitational potentials of the two stars and the effective potential of the fictitious centrifugal force, is

$$\Phi_R = \frac{GM_1}{(x^2 + y^2 + z^2)^{1/2}} - \frac{GM_2}{((x - a)^2 + y^2 + z^2)^{1/2}} - \frac{1}{2} \Omega_{\text{orb}}^2 [(x - \mu a)^2 + y^2] \tag{1.2}$$

where $\mu = M_2/[M_1 + M_2]$ and $\Omega_{\text{orb}} = 2\pi/P_{\text{orb}}$

from equations 1.1 and 1.2

$$\Phi_R = \frac{GM_1}{a} F \left( \frac{x}{a}, \frac{y}{a}, \frac{z}{a}, q \right). \tag{1.3}$$

where $q$ is the mass ratio $M_2/M_1$

This suggests that the shape of the Roche equipotentials, $\Phi_R = \text{const}$, are functions of $q$ and their scale is determined by $\Omega_{\text{orb}}$. The Roche equipotential sections in the plane of the orbit ($z = 0$) for $q = 0.5$ are shown in the Figure 1.2. The distortion from spherical shape depends on mass ratio of the stars and separation between them.
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The Roche-lobe filled secondary can not expand any further. Instead, gas from secondary atmosphere can escape through Langragian point $L_1$ into the Roche lobe of the primary. The escaped gas flows in a stream like shape. This stream of gas is deflected by the Coriolis effect. As the gas moves closer to the primary its velocity increases from original sonic velocity to highly supersonic.

1.2.4 Disc

As the stream moves in the primary lobe it reaches the point of closest approach from primary which is at distance $r_{\text{min}} \sim a0.0488q^{-0.464}$ (Lubow and Shu, 1975). This distance is much larger compared to the radius of the compact primary. Moreover, the particles of gas of a stream does not have sufficient energy to cross the lobe at any point. Thus the trajectory lies entirely within the Roche lobe of the primary and whenever the particle approaches the lobe its velocity reduces. Therefore, the stream passes by the primary and the trajectory lying entirely in the orbital plane of the binary. Eventually stream collides with itself at a point well within the Roche lobe and relatively close to the primary. This collision at supersonic speeds shocks the gas to high temperature, thereby radiating away the relative kinetic energy of the impact. Due to conservation of the angular momentum and the fact that the circular orbit has the least energy for a given angular momentum, the stream of gas finally forms a ring of gas.

Any viscous processes that are present in the gas will generate heat from this shearing flow. As the heat is radiated, some of the particles move towards the primary. At the same time few particles will move away from the primary in order to conserve the angular momentum. This the ring spreads into a disc. Usually the disc is well inside the primary Roche-lobe and hence virtually free from the gravitational effects of secondary. However, outer regions of the disc may suffer tidal interaction. Throughout most of the disc the annular velocity of the particles will differ negligibly from the Keplerian circular value $\Omega_K(r) = \left( \frac{GM}{r^2} \right)$. The whole
process is shown in Figure 1.3

1.2.5 Bright Spot

When a stream of gas impacts onto the outer rim of the disc at supersonic speeds, a shock-heated area is created which may radiate considerable amount of energy compared to total energy at optical wavelengths. Since the path of the stream gas is curved, the location of bright spot is considerable deviated from the line joining the centers of primary and secondary. The exact location of bright spot can be calculated by the interaction of the stream trajectory with the outer edge of the disc which depends on the radius of the disc and the stream trajectories which is mostly the function of mass ratio.

It has been observed from eclipse analysis that the spot can be relatively stable for the some weeks or can move significantly on time scales of an hour (Cook and Warner, 1984; Cook, 1985; Wood et al, 1986).

1.3 Magnetic Cataclysmic Variables

When the WDs of CVs are moderately or highly magnetic ($B \geq 1 MG$), the accretion scenario of the system is much different compared to systems with weakly magnetic WDs. Such systems with magnetic WDs are known as magnetic CVs (mCVs). mCVs are a small subset of CVs ($\sim 10\% - 20\%$, Downes et al, 2005; Ritter and Kolb, 2003) and fall into two categories: polars (or AM Her types after the prototype system), intermediate polars (IPs or DQ Her types). However, sometimes a third category, Asynchronous polars (APs), is also counted, but yet not fully accepted. The WDs in polars possess such strong magnetic fields that they can synchronise the whole system (see King et al, 1990 for the polar synchronisation condition), yielding $P_{\text{orb}} = P_{\text{spin}}$. Figure 1.5 shows the schematic view of Polar stars. The strong magnetic field in these systems is confirmed by strong optical polarization. Accretion in polars is thought to follow the magnetic field lines of the
Figure 1.5 Schematic diagram of Polars. Note that the accretion stream directly connects with magnetic field lines of white dwarf and hence disc does not form.

WD straight from the L@ point onto the WD magnetic poles, and no accretion disk is expected (for a review of polars see Cropper (1990)). APs on the other hand are out of synchronization by only a few percent, and it is not known exactly why this is. One suggestion is that these systems are polars which have had a recent nova event kicking them slightly out of synchronism Warner (2003). For IPs the lack of strong optical polarization implies a much weaker magnetic field, not powerful enough to synchronize the secondary (for a review of IPs see Patterson (1993)). In these systems material leaving the L1 point usually forms an accretion disc up to the point where the magnetic pressure exceeds the ram pressure of the accretion gas (See Figure 1.6). From these point onwards the accretion dynamics are governed by the magnetic field lines, which channel the material onto the WD magnetic poles. The nature of these system is confirmed by the detection of coherent X-ray modulation associated with the spin period of the WD.

1.3.1 Polars

When the magnetic field is strong enough to synchronize the white dwarf spin with orbital period, the system is known as the Polars or AM Her stars. Accretion
in such systems is directly through the magnetic field lines of WD which directly accretes near the magnetic poles. The magnetosphere of such systems extends above the circularization radius and thus do not allow accretion stream to form a disc. Accreting material initially moves in free falling path up to the point where the ram pressure equates the magnetic pressure and then magnetic field lines drives material in a channeled like shape to the regions near magnetic poles. However, in some systems the White dwarf have even stronger magnetic field which controls the accretion flow right from the L1 point. AR UMa is such a system in which 230 MG WD controls the accretion flow right from L1 point.

As the accreting plasma reaches near the white dwarf, the pressure of converging field lines squeeze them to divide into dense blob of material. Magnetic field do not penetrate such dense blobs because of screening effect. finally, the magnetic field force blobs to change their direction of motion, causing the inter-collision which produce the shock. Energy of blobs dissipated and radiated away. Energy from shock region radiated in the form of X-ray or UV radiation.

The ionized material in polars spirals around the magnetic field lines while moving towards WD which results in emission of cyclotron radiation. the optical spectra of polars are, thus, contaminated by cyclotron humps. Modelling of such humps allows us to infer the magnetic field strength of the WD. Moreover, cyclotron radiation is polarized by nature. As cyclotron radiation can be as much as 50% of the total light of polars, such systems are the most polarized sources in the sky. in 1976, Santiago Tapia first detected the high level of polarization in AM Her star, giving them the name "Polars". Polarization is very important to the study of AM Her stars: from the ratio of linearly to circularly polarized light one can infer the angle between the line of sight and the magnetic axis and how it varies with orbital phase. This gives the knowledge of the binary inclination and the tile between the magnetic and spin axis. Modelling the polarization can also yield the strength of the field.

Another characteristic of Polars is the white dwarf spin is synchronized to
the orbital period of the system i.e. $P_{\text{spin}} = P_{\text{orb}}$. The synchronization of white dwarf in Polars are thought to be the interaction of the strong magnetic field of the white dwarf with the field of the secondary star. The fields can interact where they meet, entangling their field lines. Thus if one is spinning faster the joint field lines will be wound up, increasing their tension and stored energy and creating a drag force. This drag acts as a torque on the WD, counteracting the effect of accretion and slowing it down into synchronous rotation.

However, some polars are not strongly synchronized, known as Asynchronized Polars (APs). ~ 10% of Polars are APs. White Dwarf in APs is asynchronized to fraction of percentage of orbital period. Asynchronization can result if the synchronizing torque is not quite strong enough to do its job. For instance, if the white dwarf field is weaker than average, or the binary separation is larger. The observed asynchronous systems may also be in short term departure from synchronism. Nova eruption event may disturb the synchronism and put system out of sync condition.

1.3.2 Intermediate Polars

Another small subgroup of magnetic CVs are Intermediate Polars. The magnetic field of White Dwarf in IP is not so strong to synchronize WD spin with Orbital period but strong enough to disrupt the accretion flow before they reach onto the white dwarf surface. Generally, the WD of IP contains 1- 10 MG or more. Such an intermediate value of magnetic field gave rise to the name ”Intermediate Polars”. White Dwarf of IP spins considerably fast compared to orbital period of the system. Like Polars, the supersonically accreting material forms a shock before reaching onto the WD surface and radiates away lots of energy. This radiation is in the form of Hard X-rays and UV radiations.
1.3.2.1 Eclipsing Systems

Out of all confirmed IPs only two are eclipsing systems. The prototype system DQ her and XY Ari. Out of these, XY Ari is hidden behind a dark cloud so not visible in optical light. However, it is bright enough to be observed in near-infrared K band light. However, Brian Warner and Patrik Woudt 2009 claimed that V597 Pup is intermediate polar system showing eclipse. But this claim is not yet confirmed by any other observations. However some systems like EX Hya shows partial eclipse of disc.

1.3.2.2 The Accretion Flows and Evolution of mCVs

Norton and collaborators have published series of papers (Norton et al., 2008, 2004b). Using numerical simulations they demonstrated in these papers that four types of accretion flows are possible for accreting magnetic Cataclysmic Variable stars. It was shown by then that the fundamental parameters determining the
mode of accretion flow is the ratio of spin-to-orbital period of the system. Their results will be reviewed in this chapter. This results will help understand some of the observations presented in this thesis.

Norton et al. (2008, 2004b) have shown that in the case of mCV the orbital and spin parameters tend to evolve towards a spin-to-orbital equilibrium. For any given orbital period, mass ratio and magnetic field strength of white dwarf, there exists a spin period at which gain and loss of angular momentum is balanced in the binary. Assuming a mCV is spinning very fast, a lot of the material latching onto the field lines will be expelled by the rapidly spinning magnetic WD. Thus, material will carry angular momentum and WD will slow down. Opposite to this scenario, if the WD is spinning very slowly, most of the material will transfer extra angular momentum to the WD when accrete onto it and WD will spin up. An equilibrium is achieved inbetween where the WD is in a state of accretion and ejection. Therefore, in general, mCVs are expected to remain close to this equilibrium when considering long timescales. However, the WD may be spinning up or down in short time scale as shown by Patterson (1993). However, the spin-up or spin-down rates observed within IPs correspond to much longer timescales than those expected to reach equilibrium. This suggests that the systems swing around their equilibrium occasionally, possibly due to variation in mass loss. This phenomenon is also predicted by the numerical simulations carried out by Norton and collaborators. Broadly speaking, they have shown that four types of flows are possible within IP systems, Characterized as one of:

**Propellers** in which most of the transferred material from the secondary is magnetically propelled away from the system by the rapidly spinning magnetosphere of the WD.

**Discs** in which most of the material forms a circulating flattened structure around the WD, truncated at its inner edge by the WD magnetosphere where the material latches to the magnetic field lines before accreting on to the WD surface.
Figure 1.7 Relation of spin period and magnetic moment of white dwarf at various orbital period from simulation of Norton 2008. Various regions are marked with boundaries. Spin and magnetic moment of the white dwarf define the mode of accretion. D for disc, P for Propeller, S for Stream and R for ring accretion. Though the boundaries are drawn as sharp line, actually they are very blurred. Note the two triple points where the system can be in equilibrium.
Figure 1.8 Various mode of accretion is shown as a function of spin period and magnetic moment of white dwarf. This simulation results are for 4 hour orbital period. From Norton 2008.
Streams in which most of the material latches onto field lines immediately and follows these on a direct path down the WD poles.

Rings in which most of the material forms a narrow annulus circling the WD at the outer edge of its Roche lobe, with material being stripped from its inner edge by the magnetic field lines before being channeled down the WD surface.

As mentioned before, the main parameter in determining the type of flow of accretion in a system is the spin-to-orbital period, however mass ratio and magnetic field strength of the WD also important. Figure 1.7 taken from Norton et al. (2008), shows sample of the results from their simulations for systems with mass ratio of $q = 0.5$. Each panel is for a particular orbital period. The drawn boundaries are there for reference, in reality they are quite blurred. The planes all divide into four regions. This marks the boundary between accretion flow types that will generally spin-up (streams) and accretion flow types that will generally spin-down (propellers). In general, if an IP system is found in a region of the parameter space where it is fed by stream accretion it will spin-up the WD and move it downwards in the plane in Figure 1.7 towards the equilibrium line. Opposite to that if an IP system falls in a region of parameter space where the accretion flow is in form of a propeller, it will spin-down the WD and so move it up towards the equilibrium line. We note that both the ring and stream accretion will keep the WD close to spin equilibrium through a combination of accretion and ejection of material. we also point out the two triple points of equilibrium from this figure at which all systems are trying to reach, according to simulations. If an IP reaches one of these point then it is prone to stay there forever and not become a totally synchronized polar.

Figure 1.8, taken from Norton et al. (2008), gives an idea of different type of accretion flow. One can see from this that close to these two triple points i.e. stream-disc-propeller triple point (at about $P_{\text{spin}}/P_{\text{orb}} = 0.1$) and the stream-ring-propeller triple point (at about $P_{\text{spin}}/P_{\text{orb}} = 0.6$), the equilibrium flows are a combination of the various flow types. In each case the angular momentum
accreted by the WD is balanced by an equal amount lost from the system via material magnetically propelled away: the definition of an equilibrium spin period.

### 1.3.2.3 Accretion Geometry

One of the most debatable issue for the case of IPs is the accretion geometry of the system or mode of accretion at which material accretes onto white dwarf. The major question is 'Do IPs contain discs?' The simplest picture of IPs is that they have a partial (and fully Keplerian) accretion disk, truncated by the magnetic field of the white dwarf. However, the concept of accretion via disc is questioned time to time. Haueury, King and Lasota (1986); King, Mouchet and Lasota (1991) presented theoretical arguments against this idea. They suggested that most IPs were discless, with the accretion stream falling until it encountered the magnetosphere directly. They argued that, observationally, discless systems would be distinguished by X-ray modulations over the orbital cycle, since in a stream-fed system the accretion sites would lie 'beneath' the stream, and so be localized in orbital phase.

The most promising case of such 'discless' stream-fed accretion is V2400 Oph. This system is at a low inclination of only \( \sim 10^\circ \), so we only ever see the 'upper' magnetic pole (Buckley et al., 1995; Hellier and Beardmore, 2002). Modulation of circular polarized light suggests that the spin period of the white dwarf is 927 seconds. The X-ray flux, however, varies with 1003 seconds. Considering the orbital period of the system as 3.4 hours derived from optical spectroscopy, 1003 seconds can be simply explained as the beat period between spin period of WD and orbital period of the system. The modulation of X-ray light at beat period is explained as follows: The accretion stream, which is fixed in the binary system, is flipping between two poles as the white dwarf spins. As the stream flips to the hidden, lower pole, the X-ray flux drops, resulting in a beat-cycle pulsation which dominates the X-ray light curves (Figure 1.9). The idea is supported by optical spectroscopy, where observed velocity changes over the beat cycle match well to a
Figure 1.9 X-ray light curve of V2400 Oph. X-ray light is only modulated at beat period of spin and orbital period.

white dwarf (Figure 1.10).

Despite the strong case of V2400 Oph, it is believed that most IPs fed via a partially developed disc. The reasons are as follows: High inclination systems like XY Ari and EX Hya shows eclipses which provides the spatial probe of the accretion flow, which strongly supports the presence of disc. Secondly, the optical spectroscopy shows the S-waves which are similar to those seen in non-magnetic CVs, where they arise from the impact of the accretion stream with the disc. The velocities and phasing of the S-waves imply a location in the outer half of the primary’s Roche-lobe, suggesting that the stream collides with a disc. Moreover, the X-ray orbital modulations seen in many IPs are also often (if not always) caused by azimuthal structure of the disk (Hellier, 1993; Parker, Norton and Mukai, 2005).

In order to understand the mode of accretion in IPs we need to consider three important numbers: $R_{min}$, the minimum distance between the ballistic trajectory from the L1 point and the white dwarf; $R_{mag}$ the magnetospheric radius; and $R_{cir}$, the circularization radius, where the specific angular momentum of the material in a Keplerian disk would equal that of the co-rotating material at the L1 point.

A disk will definitely form if $R_{min} > R_{mag}$, while a disk will definitely disappear if $R_{min} < R_{mag}$. The case of $R_{min} < R_{mag} < R_{cir}$ is tricky, since a disk should not be able to form but once formed, it can remain undisrupted. Since $R_{mag}$ is determined in part by the accretion rate, an episode of high accretion rate
Figure 1.10  Trailed spectra of V2400 Oph is shown. Vertical axis is Beat Phase and Horizontal axis is Velocity in $Kms^{-1}$
can establish a disk in this regime. Depending on the mass ratio of the binary, 
\( P_{\text{spin}} / P_{\text{orb}} \sim 0.1 \) corresponds to this regime.

Disc-overflow accretion: Even in systems where a spin-cycle pulsation domi­
nates the X-ray light curves, a weaker beat cycle pulsation is often seen (e.g. Buck­
ley and Tuohy (1989); Hellier (1991, 1998). These have been interpreted as show­
ing that most of the accretion flow through an accretion disc, but that part of the 
stream overflows the disc and so encounters the magnetosphere directly, giving rise 
to the beat-cycle modulation. The idea that overflow occurs in CV is supported 
by theoretical modelling (e.g. Lubow (1989); Armitage and Livio (1998)).

Lubow and Shu (1975) showed that the stream is generally thicker than the 
disc rim, allowing the part of the stream to continue onwards. This idea has been 
used to explain features of LMXBs (Frank, King and Lasota, 1987) and nova-likes 
(Shafer, Hessman and Zhang, 1988). Evidence that this occurs in an IP system FO 
Aqr comes from the strong absorption features seen in its lines (Hellier, Mason and 
Cropper, 1990). These are similar to the phase 0.5 absorption feature in SW Sex 
stars, which Hellier & Robinson (1994) suggested originate in the stream during the 
free fall part of its trajectory over the disc. FO Aqr is the best studied example of 
a system showing disc-overflow accretion. The X-ray pulsation at the spin period 
is always largest, but there is often (though not always) an additional pulsation at 
the beat period (Hellier, 1991; Norton et al., 1992; Hellier, 1993; Beardmore et al.,
1998). The implication is that the overflow is variable, occurring often but not 
always. FO Aqr can be taken as an example of the stars AO Psc, V1223 Sgr and 
BG CMi, which have all shown a weak beat cycle pulsation in at least one X-ray 
observation (Hellier, 1998). For the overflow stream to directly accrete, something 
like this condition: 
\[ R_{\text{min}} < R_{\text{mag}} < R_{\text{cir}} \]
must be met (Hellier, Garlick and Mason, 1993).

This means that systems such as EX Hya are hard to understand in the stan­
dard, Keplerian, accretion disk picture. A series of papers based on the diamagnetic 
blob picture, however, explain such systems (Wynn and King, 1995; Norton, Wynn
and Somerscales, 2004a; Norton et al., 2008). So far, there are 2 other confirmed IPs in this regime; other candidates have been proposed, but not been confirmed yet.

1.4 Outbursts in Intermediate Polars

The defining characteristics of the Cataclysmic Variables (CVs) is occurrence of outbursts. During these outbursts the CVs brighten by several magnitudes in a short duration of few hours and subsequently slowly decline in brightness over time intervals of a few days to few years. The CVs are divided into various subclasses based on their outburst amplitude and recurrence time scales.

Here we discuss the outbursts observed in one of the classes of CVs, namely, the Dwarf Novae. It was a mystery since the discovery of U Gem and SS Cyg how the dramatic event of outburst happens. It is only in last few decades of 20th century that the understanding has developed about the mechanism for the dwarf nova outbursts. First clue came from the very high speed photometry of some of the eclipsing CVs showing outburst. These results show that the disc brightens up during the outburst. Two mechanisms have been proposed to explain the outbursts, namely, thermal instability of the disc and the enhanced mass transfer from unstable secondary. Over the years, the former mechanism is the more favored mechanism though it is not fully accepted by the IP community. In 1974, Osaki gave the concept of thermal instability of the disc as a mechanism involved in dwarf nova outburst. He argued that if the mass transfer rate from the secondary star to the disc is at constant rate and is higher than the rate of mass accretion from disc to white dwarf then the material will accumulate in the disc. The increasing surface density of the disc leads to the enhanced viscosity in the disc. The disc becomes more opaque to the incoming radiation from the white dwarf and heats up. Finally the disc becomes unstable and the angular momentum transport in the disc increases drastically. The material in the disc spreads outward as well as
inward towards the white dwarf to increase the size of the disc. This enhances the accretion on to the white dwarf and consequent increase of the luminosity of the system. Finally, the disc loses most of the accumulated mass and comes back to the quiescence level. Again, as the material starts accumulating in the disc from the secondary star and process repeats. Another model to explain outburst was mainly developed by Geof Bath. This model explains the outburst as a consequence of sudden enhancement of mass transfer from the secondary star which finally leads to the increase in luminosity of the system. However, several observational evidences and theoretical models favour the disc instability over enhanced mass transfer. It is pertinent to point out that the outbursts observed in few CVs are still in support to the later model, namely, the enhanced mass transfer from the secondary star.

Among 36 confirmed IPs, 9 of them sometimes show sudden brightening from quiescence level. Such phenomenon of rapid brightening followed by decaying to quiescence level is known as outburst. These IPs are V1223 Sgr, TV Col, EX Hya, XY Ari, YY Dra, GK Per, HT Cam, V1062 Tau and DW Cnc.

Table 1.1 List of IPs showing outburst activities

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>IP</th>
<th>Orbital period</th>
<th>Spin period</th>
<th>Outburst duration</th>
<th>Outburst amplitude at V band</th>
<th>Interval between two outbursts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>V1062 Tau</td>
<td>9.982</td>
<td>3780</td>
<td>1-2</td>
<td>1 mag</td>
<td>few months?</td>
</tr>
<tr>
<td>2</td>
<td>TV Col</td>
<td>5.487</td>
<td>1910</td>
<td>0.5</td>
<td>2 mag</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>V1223 Sgr</td>
<td>3.366</td>
<td>745</td>
<td>0.5</td>
<td>2 mag</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>EX Hya</td>
<td>1.633</td>
<td>4022</td>
<td>3.5</td>
<td>2 mag</td>
<td>600?</td>
</tr>
<tr>
<td>5</td>
<td>GK Per</td>
<td>47.92</td>
<td>351</td>
<td>80</td>
<td>3 mag</td>
<td>3 years</td>
</tr>
<tr>
<td>6</td>
<td>HT Cam</td>
<td>1.43</td>
<td>516</td>
<td>1.5</td>
<td>4 mag</td>
<td>147</td>
</tr>
<tr>
<td>7</td>
<td>DW Cnc</td>
<td>1.435</td>
<td>2315</td>
<td>2-4</td>
<td>4 mag</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>YY Dra</td>
<td>3.96</td>
<td>529</td>
<td>5</td>
<td>5 mag</td>
<td>364 days</td>
</tr>
<tr>
<td>9</td>
<td>XY Ari</td>
<td>6.06</td>
<td>206</td>
<td>5</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

References: GK Per Evans et al. (2009); Crampton, Fisher and Cowley (1986); Watson, King and Osborne (1985) YY Dra Šimon (2000b); Andronov et al. (2008) TV Col Schwarz et al. (1988); Hudec, Šimon and Skalicky (2005); Hutch-
Outburst properties like amplitude and time to come back to quiescence varies vastly from system to system. Outburst amplitude ranges from 0.5 mag to 5 mag and outburst duration ranges from less than a day to 5 days with exception of GK Per in which outburst lasts for 50 to 100 days. GK Per is also exceptional in terms of outburst recurrence time of about 3 years which is higher compared to that of other IPs. However, these behaviors are well understood considering the fact that GK Per is very long orbital period system with 48 hours orbital period. It is clear now that this system contains highly evolved secondary star and a well developed disc. Outburst properties of this system can be well explained by disc instability model.

YY Dra, XY Ari, HT Cam, DW Cnc are the other IPs which show relatively long and high amplitude outburst. These systems are believed to have a partially developed disc. Instability in this disc is believed to be responsible for the outburst in these systems.

However, few systems put some challenges to the disc instability model of outburst. These systems are TV Col, V1223 Sgr, V1062 Tau and EX Hya. These systems are either do not contain the disc at all or contains disc too weak to explain the outburst. Therefore the possible cause of rapid short amplitude outbursts in these systems is enhanced mass transfer from secondary star.
1.5 Secondary Star of Cataclysmic Variables

Knowledge of secondary star and its various parameters help us to understand the evolution scenario of CV. Two obvious key features of orbital period distributions of CVs are: The famous CV period gap exists between period range \(2\text{hrs} < P_{\text{orb}} < 3\text{hrs}\) and the period minimum around \(P_{\text{min}} \sim 80\text{minutes}\). The most important requirement for any successful model of CV evolution is that it must provide a natural explanation for the origin and location of these features.

In early 80s, people put forward a model based on disrupted magnetic breaking scenario (Rappaport, Joss and Webbink, 1982; Spruit and Ritter, 1983). This model explained the basic properties of period distribution up to a good extent. It accounts for the existence of the period minimum and the period gap. For this reason, this model is considered as a standard model.

In the standard model it was assumed that the secondary star in a CV becomes fully convective. This happens at around \(P_{\text{orb}} \sim 3\text{hours}\). At this stage the magnetic breaking mechanism will abruptly switch off. At this point in its evolution, the donor star has been driven slightly out of thermal equilibrium. Therefore it is somewhat oversized for its mass. The switching off event of magnetic breaking reduces the mass loss rate so secondary star contracts which cause it to lose contact with the Roche lobe altogether. The upper edge of the gap thus marks a cessation of mass transfer in CVs. According to the standard model, CVs then evolve through the period gap as detached systems. During this detached phase, the binary orbit and Roche lobe continue to shrink, since there is still ongoing angular momentum loss due to gravitational radiation. However, provided the thermal relaxation of the donor is faster than the shrinkage of the Roche lobe, the donor manages to relax all the way back to its thermal equilibrium radius. In practice, this condition is met, so long as the angular momentum loss rate is reduced by at least a factor 5-10 at the upper gap edge. The bottom edge of the period gap then corresponds to the location where the Roche lobe radius catches up once again to
the Thermal equilibrium radius of the donor. At this point, mass transfer restarts, and the system emerges from the gap as an active CV once more.

This standard model also explains another feature of period distribution which is a sharp cut-off at $P_{\text{min}} \sim 80 \text{minutes}$. This is again associated with the secondary star's mass loss induced loss of thermal equilibrium. Secondary's thermal time scale increases much faster than the time scale on which it losses mass. This drives secondary away from thermal equilibrium, the size of the binary orbit must increases again and the system that have passed beyond $P_{\text{min}}$ are evolving back towards longer periods. Such systems are often called Period bouncers.

Another interesting conclusion is as follows: Since there is no mass transfer in the gap, the donor mass just above and below the gap must be the same. We also know that the donor at the bottom edge is in or near equilibrium. In order to fulfill these criteria, donors at the upper edge of the period gap have to be oversized by $\sim 30\%$ relative to equal-mass, isolated MS stars.

However, since last few years, it was recognized that there may be problems with this explanation. Particularly following issues have often been noted as serious challenges for the standard model.

The minimum period of 65 minute predicted by standard model is significantly shorter compared to the observed one. Until recently, the observed value was usually estimated to be around 75 minutes, based on the observed cut-off in the period distribution of available CV Sample. In 2009, Gansicke et al. (2009) has located the period spike at $P_{\text{min}} \sim 82 \text{minutes}$ is SDSS CV sample. This made the discrepancy even worse. Another issue is the standard model predicts that the Galactic CV population should be complete dominated by short period CVs and period bouncers, possibly in the ratio 1:30:70 for long period CV, short period CV and period bouncers, respectively Kolb (1993). However, observations do not support such a small ratio (Patterson, 1998). Even if selection effect is taken into account this theoretical ratio can not match with observations (Pretorius, Knigge and Kolb, 2007; Pretorius and Knigge, 2008a,b).
In a series of papers, Christiaan Knigge and his collaborators have tried to answer these problems by developing a model which overcomes the limitations of the standard model (Knigge, Baraffe and Patterson, 2011; Knigge, 2006). In this process they have discussed the comparison between the secondary stars of CVs with normal isolated main sequence stars. They observationally found that secondary stars of CVs are indeed bit larger and cooler compared to the isolated main sequence stars. Moreover, they developed an empirical mass radius relationship for secondaries (Figure 1.11). From their empirical relationship they found that mass radius relation of secondaries has a discontinuity at $M_2 \sim 0.2M_\odot$. This discontinuity separates short-period and long period CVs.

By combining the observed mass radius relation with a theoretical mass-effective temperature of secondaries, they have also been able to construct a complete, semi-empirical donor sequence for CVs that provides all physical and photometric parameters of CV secondaries as a function of only $P_{\text{orb}}$. This includes the semi-empirical relationship between spectral type of secondary and orbital period of the system (Figure 1.12). Their model also reproduces the minimum period limit value i.e. 82 minutes which is in good agreement with observed one. The value
Figure 1.12 Relation between spectral type of secondary star and orbital period of the system is shown. From Knigge 2006.
predicted by standard model is significantly shorter. Their model also predicts the correct location for the upper edge of the period gap, while the prediction from standard model is significantly longer value.

1.6 Objectives of the Study

There are several aspects in the study of Intermediate Polars that need additional observational inputs at various wavelengths. Such a study is required to understand the properties of individual components of the underlying system like the secondary star that is losing mass and interesting physical processes related to the accretion geometry and episodic enhanced mass transfer. Some of the issues related to secondary star and accretion geometry are listed below:

Secondary stars: Secondary star or mass donor star directly or indirectly effects the system geometry. Solar type activities of secondary star is detected in GK Per in the form of modulation of light at time scale of decades (Ak, Ozkan and Mattei, 2001; Bianchini, 1990; Warner, 1988). Rate of mass transfer (\( \dot{M} \)) from the secondary star and its changes with time effects the accretion scenario. Study of secondary star of intermediate polars is essential to understand the system.

Accretion parameters: System parameters like orbital and spin periods, inclinations, spectral type of secondary star and magnetic moment of white dwarf are essential to know in order to understand the system. Some parameters like true spin period of white dwarf among two harmonic values, fractional area of magnetic accretion onto white dwarf surface, height of the shock region, etc. are issues of debate.

Modes of accretion: Intermediate polars are unique among all CVs as they may contain partially developed disc along with magnetically accretion curtain shaped accretion on white dwarf. Therefore, both disc-fed accretion and stream-fed accretion are possible mode of accretions. Few systems show combination of both i.e. disc overflow accretion. Moreover, some systems are believed to show change in
accretion mode with respect to time. Hence, understanding of modes of accretion in IPs and their change needs additional investigations.

Change in accretion geometry during outburst A small number of IPs undergo small dwarf-nova type recurrent outbursts. Studies of IPs in outburst clearly indicate dramatic change in accretion geometry. As discussed in section 1.4, GK Per, XY Ari and EX Hya showed increased X-ray flux and spin pulse amplitude during outburst whereas YY Dra showed increased X-ray flux with decreased amplitude of spin pulse during outburst.

Long and short term Quasi-Periodic Oscillations Quasi-Periodic Oscillations has been detected at X-ray and optical wavelengths in small number of intermediate polars. The period of such oscillations are detected from few 10s of second to few thousand of second (e.g. GK Per, Mazeh et al. (1985); Hutchings and Cote (1986)). Several models are proposed to explain such oscillations but the debate yet going on.

In order to address these questions, intermediate polars are vastly studied in X-ray, ultraviolet and optical regime. Radiation coming from intermediate polar is modulated at various period, mainly due to the asynchronous rotation of the magnetic white dwarf primary. Such modulations at orbital period, spin period and various beat periods of orbital and spin periods are detected. Moreover, Quasi-Periodic Oscillations are also found in some objects during outburst (e.g. GK Per (Mazeh et al., 1985)) or during quiescence (e.g. DW Cnc (Uemura et al., 2002)). Presence or absence of modulations at particular periods can be used as a probe to understand the basic accretion geometry of the system.

It come to our notice that intermediate polars are not extensively investigate at infrared wavelengths. Cool main sequence secondary star is main contributor at infrared wavelengths among all binary components. However, contribution from other components are also considerably large. Partially developed disc, Magnetic accretion curtain and bright spot are also significant emitters in infrared regime. Moreover, high energetic radiation beam emitted from spinning white dwarf is
incident on such components, reprocessed and remits at infrared along with other wavelengths. IR studies of IPs would be helpful to validate these results. We have undertaken near-infrared and optical study of selected IPs in the present thesis to address the following issues.

To detect the short and long term oscillations at IR wavelengths and use them as a probe to understand the system.

To understand the binary components, system geometry, mode of accretion.

To detect modulation of different periods present in emission line spectra taken in the optical regime.

1.7 Organization of the Thesis

The thesis consists of 6 chapters. Chapter 1 gives a general introduction to the cataclysmic variables, in particular, Intermediate polars. Chapter 2 describes the telescope, instruments and the reduction precess. All data were obtained with the 1.2m Mt. Abu IR telescope and 2m Himalayan Chandra Telescope of Indian Astronomical Observatory. This chapter also describes in detail various techniques used in the time series analysis of near-infrared photometric and spectroscopic reduction. Chapter 3 presents the near-infrared lightcurve and phase resolved optical spectroscopic observations of the intermediate polar YY Dra. Orbital period of the system is determined with higher accuracy and an improved ephemeris is presented. A kilo-second QPO is detected which is interpreted as reprocessing on a rotating dense blob in the partial disc of YY Dra. The outburst recurrence time is determined using recent additional data and a lower limit to the outburst recurrence period is presented. Chapter 4 discusses the near-infrared photometric observations of Intermediate Polar WX Pyx. The Nir observations showing clear modulation at spin period are presented for the first time. The system parameters like spectral type of the secondary, distance, magnetic moment of the white dwarf, and indication of disc-fed accretion are presented. Chapter 5 describes the study of
rapid oscillations detected at near-infrared photometric and optical spectroscopic observations of three Intermediate Polars namely GK per, V709 Cas and DW Cae. The IR light curve of March 2010 outburst of GK Per and its analysis is presented. We detected QPO at period \(\sim 378\) seconds in J band near-infrared photometric data. In case of V709 Cas we detected oscillations at spin period of magnetic white dwarf and its first harmonic. Moreover, a QPO at period range 1700-2100 second is detected in near-infrared photometry. We found modulations at spin and beat periods in J band photometry of DW Cae. A signature of modulations at orbital period of the system is also detected in the cleaned spectrum. Chapter 6 is devoted to the summary and future plans for the work presented in the thesis. The radial velocity and near-infrared photometric data are presented in tabular form in the appendix. Considering the large volume of near-infrared photometric data of YY Dra, the same is available at www.prLres.invjoshi.