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FAST VARIABILITY IN COMPACT BINARIES

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RESUMEN

La variabilidad rápida es una de las características fundamentales de los procesos de acrecimiento en objetos compactos, en escalas desde enanas blancas a agujeros negros supermasivos en núcleos de galaxias activas. El estudio de esta variabilidad permite analizar en detalle la dinámica de los flujos de acrecimiento, la estructura del disco de acrecimiento, la rotación del objeto compacto, así como varios modos de oscilación. Las binarias en interacción son en particular ideales para este tipo de estudios debido a su proximidad y geometría relativamente acotada. Sin embargo, la escalas de tiempo de esta variabilidad (en estrellas de neutrones y agujeros negros) son del orden de segundos o menos. Esto implica la necesidad de grandes telescopios de nueva generación, tales como el GTC, combinados con detectores de lectura rápida y alta eficiencia, lo que permitirá entrar en una nueva era de la astrofísica, la astrofísica de alta resolución temporal.

ABSTRACT

Rapid variability is one of the main signatures of accretion onto compact objects, on scales from white dwarfs to supermassive black holes in AGN. Studies of these variations allows the dynamics of the accretion flow, structure of the accretion disk, spin of the compact object, and various oscillation modes to be probed in detail. Interacting binaries are ideal for this work because of their proximity and constrained geometry, but the variability timescales (for neutron stars and black holes) can be seconds or less. Hence this requires the new generation of giant telescopes (such as the GTC), combined with high efficiency, fast detectors in order to enter the new era of "time domain astrophysics".

Key Words: **STARS: STARS: NOVAE, CATACLYSMIC VARIABLES — STARS: VARIABLES — X-RAYS: BINARIES**

1. INTRODUCTION

The importance of high time resolution observations has been clear for more than half a century with Walker's (1956) survey of cataclysmic variables (CVs) by photoelectric photometry revealing that they all exhibited fast flickering, and that some (e.g., DQ Her) were pulsators. In fact, CVs are ideal testbeds for studying the properties of accretion disks. There are many relatively nearby examples (< 100 pc) sufficiently bright to allow detailed examination with earlier generations of telescopes. Furthermore, the fundamental CV model (a white dwarf accreting material via Roche-lobe overflow from a cool, low mass, late-type star) has the dominant light source usually being the accretion disk itself, although the hot white dwarf can often be a significant additional component. Hence CVs have provided our basic knowledge of the structure and properties of accretion disks (see, for example, Warner 1995 and references therein). Replacing the white dwarf with a neutron star or black hole produces the (much rarer) low mass X-ray binary (LMXB), in which the dominant light source is now the irradiated accretion disk, since the intrinsic X-ray luminosity of an LMXB exceeds that of a CV by at least a factor 1000 (van Paradijs & McClintock 1995). In CVs and LMXBs, the orbital periods are ∼minutes to hours, spin periods are ∼seconds to minutes, and the disks undergo outbursts (because of their intrinsic thermal properties) on timescales of months to years. Time-resolved observations, over a wide range of wavelengths and on all timescales, allows all the components in such systems to be studied, with simultaneous work being particularly valuable. Interestingly, the advent of CCDs as the primary astronomical detector for op-

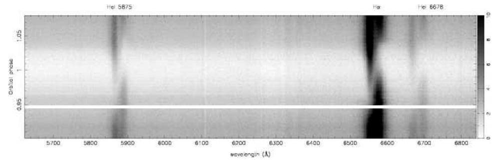

Fig. 1. Trailed Keck spectra of the eclipsing CV V2051 Oph by Steeghs et al. (2001). The double-peaked emission lines from the disk are separately occulted during eclipse ingress and egress by the secondary star. The total duration of the eclipse is about 9 min.

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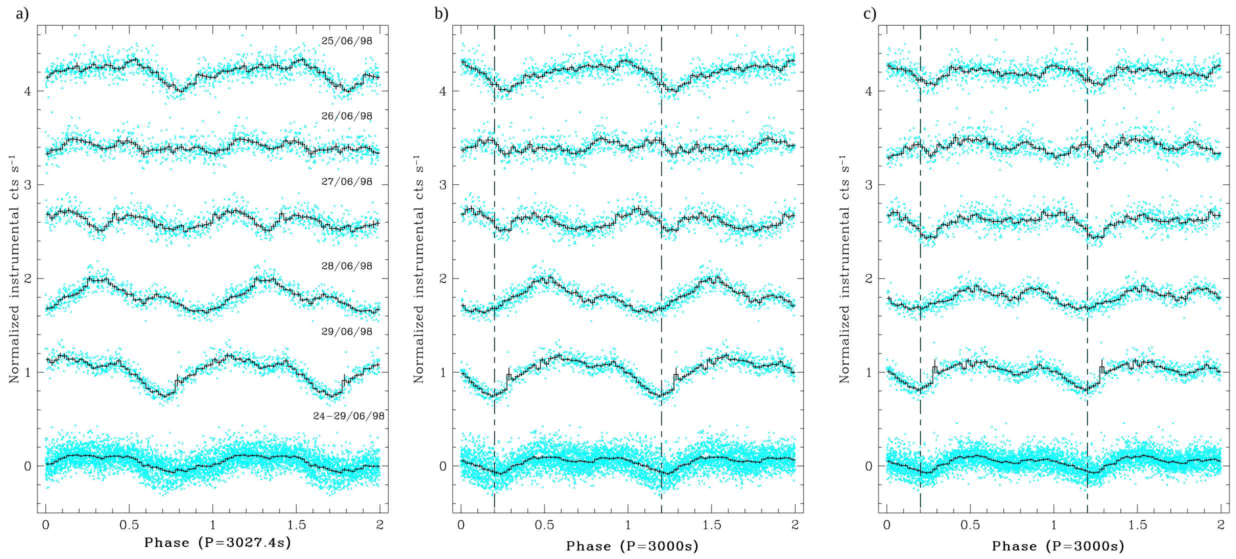

Fig. 2. NOT optical light curves of X1916−053 (Homer et al. 2001) folded on a) the 3027 s optical period and b) the 3000 s X-ray period. In c) the optical modulation is first subtracted before folding on the X-ray period. Clearly, both periods are present.

tical observations in the 1980s led to this region of the spectrum falling well behind the time resolutions offered in X-ray and UV astronomy. However, the advent of giant telescopes and new high efficiency, fast read-out devices is generating renewed interest in "time-domain astrophysics", and this is an area where the GTC has the potential to become a major player, since this region of parameter space has been largely ignored by other 8 m class observatories.

2. CATACLYSMIC VARIABLES

The short orbital periods of CVs means that the binary separation is typically only a few $R_\odot$, and even at distances within 100 pc this means that their angular extent is about a microarcsecond. Nevertheless, it is possible to resolve this structure by exploiting the changing view across the binary orbit via the technique of Doppler tomography (see Echevarria, this volume, p. 159). Furthermore, a superb example of what can be achieved in time-domain astrophysics was demonstrated by Steeghs et al.'s (2001) high speed spectroscopy of the eclipsing dwarf nova V2051 Oph. They employed a specially constructed drift-mode read-out of the Keck LRIS spectrograph to obtain a spectrum every 70 ms! A trailed spectrum plot of these data (Figure 1) shows the classical eclipse profile of the double-peaked emission lines as first one side then the other of the accretion disk is occulted by the companion.

These data were obtained primarily to investigate the nature of the so-called dwarf nova oscillations (DNOs). Usually in the range 10–30 s (and hence probably originating close to the white dwarf), they are often not coherent, and the periods can change even in the same object. No model has been able to explain all their characteristics, and they have long been thought to be analogous with X-ray quasi-periodic oscillations (QPOs) in LMXBs, which had been presumed to arise in the interaction of the inner disk with the magnetosphere of the rapidly spinning neutron star (see, for example, Belloni 2001). By having time-resolved spectra, for the first time Steeghs et al. were able to show that the continuum displayed coherent oscillations around 30 s and 56 s, whereas the emission lines displayed only the 30 s oscillations but their amplitude was modulated at 8 min! From this, they were able to construct a model for V2051 Oph consisting of a weakly magnetic white dwarf spinning at 56 s, but with two equatorial hotspots where it accreted from the disK. This oscillation then irradiated the bulge at the circularization radius (about 12 $R_{\rm WD}$) leading to the beat at 8 min. More recently Warner & Woudt (2002) have pointed out that double-frequency DNOs (see also in SU UMa systems in superoutburst) follow the same relationship to those seen in neutron star and black hole X-ray binaries. This is potentially of great significance for their physical interpretation since some models of the black hole systems invoked relativistic phenomena (e.g., Stella 2000) that can certainly not be occurring in the white dwarf binaries.

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3. WARPED PRECESSING ACCRETION DISKS

In X-ray binaries, the vastly greater irradiating flux from the accreting neutron star or black hole compact object, can lead to remarkable additional instabilities in the behavior of the accretion disk itself. This effect was first recognized in the early days of X-ray astronomy with the discovery of the 35 d on–off cycle in the 1.7 d eclipsing binary Her X-1. The tilted accretion disk precesses every 35 d, leading to regular obscuration of the X-ray source (Petterson 1977), although the detailed physics arising under irradiation has only recently begun to be understood (see Ogilvie & Dubus 2001 and references therein).

We now know that accretion disk precession is expected to be a common phenomenon in all high mass ratio ($q > 3$) interacting binaries (Whitehurst 1988) and hence should be evident in most, if not all, LMXBs. High inclination, short period LMXBs, such as X1916−053 are ideal for investigating such phenomena, but with a very faint ($V \sim 21$) optical counterpart, such studies are the domain of large telescopes. The orbital inclination of X1916−053 leads to the disk bulge (at the stream impact region) partially obscuring the central X-ray source, thereby producing "X-ray dips". Remarkably, the dip period (3000 s) is 1% shorter than the optical photometric modulation (3027 s), which is what is expected in the precessing disk model. Using the Nordic Optical Telescope (NOT), Homer et al. (2001) have shown that both periods are actually present in optical photometry (Figure 2) and propose that the longer term (∼4 d) variation in the X-ray dip light-curve arises due to a "warp" in the disk due to the X-ray irradiation. Nevertheless, the interpretation is still controversial and further progress (mapping the disk evolution on the "beat" period) requires orbitally resolved optical spectroscopy, for which the GTC is ideally suited.

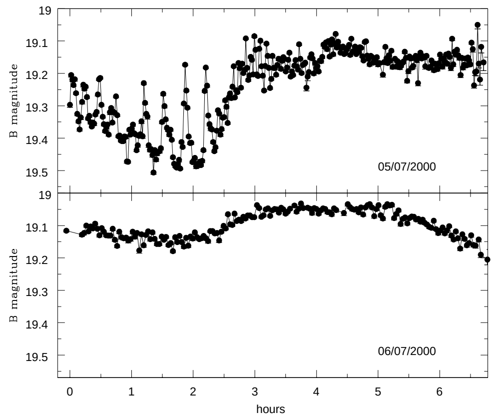

Fig. 3. Fast B band photometry of XTE J1859+226 taken on the NOT during a mini-outburst, which demonstrated 21.7 min QPO behavior that had disappeared on the following night (Zurita et al 2002a).

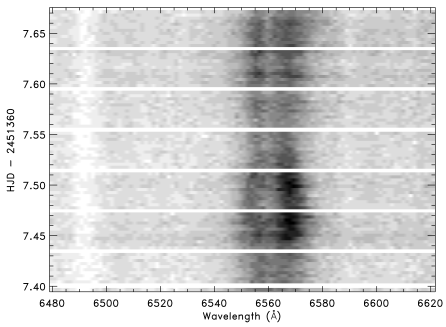

Fig. 4. Trailed spectra of V404 Cyg (Hynes et al. 2002) taken with the WHT + ISIS showing the flares and substantial variability superposed on the double-peaked Hα profile.

4. BLACK HOLE X-RAY BINARIES

4.1. *Outburst*

The soft X-ray transients (SXTs) are a remarkable class of LMXB in which their extended quiescent intervals permit detailed study of the companion star, from which accurate mass estimates can be made (Charles 2001). But their rare (usually decades) X-ray outbursts reveal a host of other properties, including the ejection of relativistic jets, and they hold the promise of providing the first unique signature for the presence of an event horizon. Nevertheless, detailed observations through outburst and decay are difficult because of their unpredictability, and yet a wide variety of phenomena are expected, some related to the (necessarily) high binary mass ratio and hence precessing accretion disk.

A large amplitude QPO at a period of 21.7 min (Figure 3) was detected by Zurita et al. (2002a) in the SXT J1859+226, during one of its "reflares" following its 199X initial outburst. The nature of this QPO is still unclear (and only photometry was obtained), but the ratio of this QPO period to the orbital period is similar to that seen in V404 Cyg, suggesting a common origin. More extensive studies of the SXT J1118+580 (Zurita et al. 2002b) showed evidence for the "superhump" expected from the precessing disk (the projected area varies on the precession period; Haswell et al. 2001) and with a period differential of only 0.3%, consistent with that expected for the black hole mass.

4.2. *Quiescence*

Whilst the companion star becomes visible in SXTs during quiescence, the accretion disk component is still present and can be a significant contributor to the light-curve. The dominant form is that of the ellipsoidal distortion of the secondary, but there is substantial additional short term variability, the nature of which can reveal details of the structure of the accretion flow. Narayan et al. (1998) have argued that, in quiescence, the inner accretion disk becomes hot and low density, leading to an advection-dominated accretion flow (ADAF) in which the accretion energy is advected across the event horizon and not radiated.

Progress in this area required time-resolved spectroscopy of quiescent SXTs, but this has only been possible to date on V404 Cyg, the brightest of this class (at $R \sim 17$). On the William Herschel Telescope, Hynes et al. (2002) obtained two nights of fast spectroscopy in which flaring behavior was seen (Figure 4). The difference between the flaring and steady spectra revealed the Hα profiles to be double-peaked and hence the entire disk (not a localized region) was participating. This led Hynes et al. to interpret these as photoionizing events driven by X-ray flares, but if true could require a modification of the ADAF scenario because of the difficulty of irradiating the disk. Further study and confirmation of this will require simultaneous X-ray observations, and larger telescopes such as the GTC for all other SXTs.

5. CONCLUSIONS

Rapid variability in accreting binaries is a powerful probe of accretion processes close to white dwarfs, neutron stars, and black holes. Detector developments in the optical (fast read-out, frame transfer) now allow high speed photometry and spectroscopy to be obtained. Large telescopes are *not* just for observing faint targets, they now allow us to explore new regions of parameter space in relatively 'bright" well-known objects—this is the *final frontier*, which giant telescopes such as the GTC can finally open.

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