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A review of the Z-track sources

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Abstract. The brightest class of low mass X-ray binary source: the Z-track sources are reviewed specifically with regard to the nature of the three distinct states of the sources. A physical model is presented for the Cygnus X-2 sub-group in which increasing mass accretion rate takes place on the Normal Branch resulting in high neutron star temperature and radiation pressure responsible for inner disk disruption and launching of jets. The Flaring Branch consists of unstable nuclear burning on the neutron star. It is shown that the Sco X-1 like sub-group is dominated by almost non-stop flaring consisting of both unstable burning and increase of $\dot{M}$, causing higher neutron star temperatures. Finally, results of Atoll source surveys are presented and a model for the nature of the Banana and Island states in these sources is proposed. Motion along the Banana state is caused by variation of $\dot{M}$. Measurements of the high energy cut-off of the Comptonized emission $E_{\rm CO}$ provide the electron temperature $T_{\rm e}$ of the Comptonizing ADC; above a luminosity of 2×10^{37} erg s^{-1} $E_{\rm CO}$ is a few keV and $T_{\rm e}$ equals the neutron star temperature. At lower luminosities, the cut-off energy rises towards 100 keV showing heating of the corona by an unknown process. This spectral hardening is the cause of the Island state of Atoll sources. The models for Z-track and Atoll sources thus constitute a unified model for low mass X-ray binary sources.

Key words. Physical data and processes: accretion: accretion disks — stars: neutron — stars: individual: Sco X-1, GX 349+2, GX 17+2, Cyg X-2, GX 5-1, GX 340+0 — X-rays: binaries

1. Introduction

The characteristic behaviour of the Z-track sources as the brightest group of low mass X-ray binaries (LMXB), was demonstrated by Hasinger & van der Klis (1989) as shown in Fig. 1. The sources, having luminosities at and above the Eddington limit, display strong physical changes via three distinct branches in hardness-intensity or colour-colour diagrams: the Horizontal (HB), Normal (NB) and Flaring (FB) branches. There are two sub-groups: the Cygnus X-2 like sources with all three tracks and the Sco X-1 like sources in which the HB is weak but flaring is much stronger. The physical changes have not been understood but the sources are important because of the detection of relativistic jets essentially around the hard apex between NB and HB. This allows investigation of jet launching by X-ray spectral studies of conditions near the neutron star when jets are formed. A complete understanding of LMXB also requires understanding of the Atoll sources having luminosities less than 10^{38} erg s^{-1} and displaying essentially two states: the Banana and Island states.

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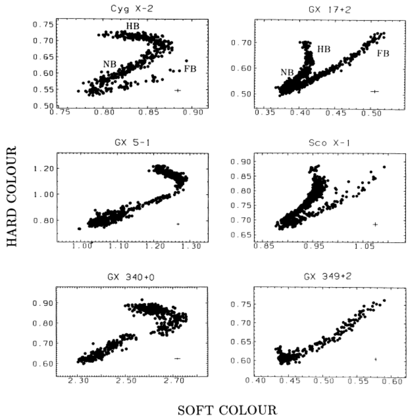

Fig. 1. The main Z-track sources: from Hasinger & van der Klis, A&A, 225, 79, 1989, reproduced with permission © ESO.

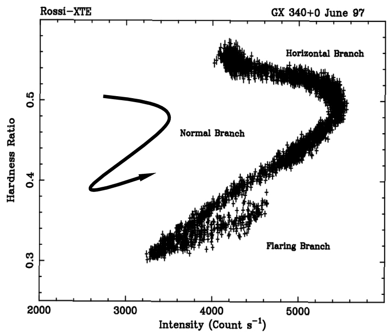

Fig. 2. A monotonic increase of mass accretion rate.

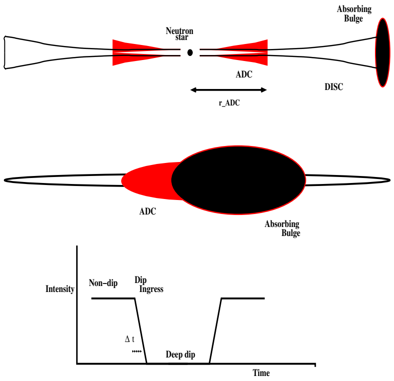

Fig. 3. Dip ingress timing: the ingress time allows the size of the extended Comptonized ADC emitter to be determined.

It was proposed by Priedhorsky et al. (1986) and by Hasinger et al. (1990) that the states of the Z-track sources might be explained by a monotonic increase of mass accretion rate $\dot{M}$ in the direction HB to NB to FB. Although this was suggested largely by rather limited evidence for an apparent increase of UV on the FB, the approach has been adopted as a standard approach. However, a rather different approach has resulted from the use of a particular spectral model based specifically on the extended nature of the Accretion Disk Corona (ADC) (Church et al. 2006).

The adoption of a realistic model of the X-ray emission is crucial to understanding and this depends on the evidence for the extended nature of the ADC. Two independent techniques have shown that the Comptonizing region in LMXB in general is extended: dip ingress timing and also measurement of the Doppler widths of highly ionized emission lines. In the high-inclination dipping LMXB, the extended nature of the dominant Comptonized emission is proven by its only gradual removal when overlapped by the absorbing bulge in the outer disk (Church et al. 1997), and the rate of removal provides the radial extent of the ADC of ~ 20 000 to 700 000 km (Fig. 3; Church & Bałucińska-Church 2004). High quality *Chandra* grating studies of highly ionized lines in Cyg X-2 such as Fe XXVI, Fe XXV, S XVI and S XIV by Schulz and co-workers (Fig. 4) gave Doppler widths equivalent to radial positions of 18 000 to 110 000, also indicating a very extended ADC (Schulz et al. 2009) in excellent agreement with dip ingress timing.

1.1. Claims that ADC not extended:

There was originally a view that the site of the dominant Comptonized emission in LMXB should be a compact central region close to the

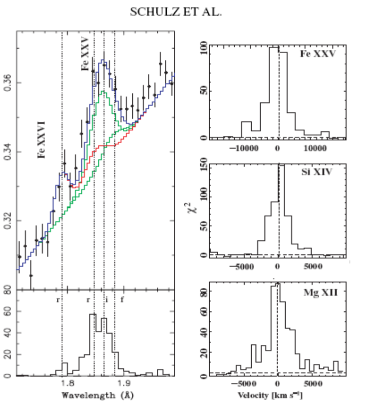

Fig. 4. From Schulz et al., ApJ, 692, L80, 2009, reproduced by permission of the authors: Doppler widths of highly ionized lines.

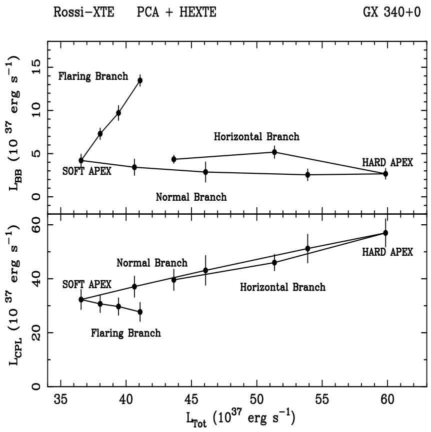

Fig. 5. The variation of emission component luminosities (Church et al. 2006).

compact object. As evidence for the extended ADC emerged, possible ways of avoiding the extended nature were suggested. Highly ionized absorption features were found in the dipping source X 1624-490 by Parmar et al. (2002) and similar features found in other dipping sources. However, Boirin et al. (2005) and Díaz Trigo et al. (2006) proposed that the X-ray absorption dips occurring at the orbital period could be modelled by a varying ionization state of absorber, and that the dipping sources could be explained without the need for an extended ADC. However, this did not take into account i) the gradual removal of Comptonized emission in dipping which proves an extended nature and ii) dipping would have to be unconnected with the bulge in the outer disk, contrary to extensive evidence. Thus such claims are not very physical.

2. The Cygnus X-2 like Z-track sources

The spectral model based on an extended ADC has a quite specific form (Church & Bałucińska-Church 2004) since the seed photons will predominantly arise in the disk beneath the ADC; in addition there will be thermal emission of the neutron star. It was found that when this model was applied in studies of spectral evolution along the Z-track in the Cyg-like sub-group (Cyg X-2, GX 5-1 and GX 340+0) the approach provided a rather straightforward explanation (Bałucińska-Church et al. 2010). The results indicated that evolution along the NB was driven by an increase of $\dot{M}$ followed by a similar decrease on the HB, while flaring consists of unstable nuclear burning. A significant result was that spectral fitting showed that 75% of the X-ray luminosity is due to Comptonized emission as seen in Fig. 5 for GX 340+0. Thus the large increase in this ($L_{\rm ADC}$) on the NB from the Soft Apex to the Hard Apex strongly suggests that $\dot{M}$ increases (contrary to the $\dot{M}$ decrease in the standard view). This is supported by the corresponding increase of neutron star temperature kT from $\sim$ 1 to more than 2 keV (Fig. 6) which shows that the radiation pressure of the neutron star increases by almost 10 times at the Hard Apex. The measured neutron star flux becomes several times the Eddington flux and we proposed (Church et al. 2006) that this disrupts the inner disk and launches jets at this part of the Z-track by radiation pressure.

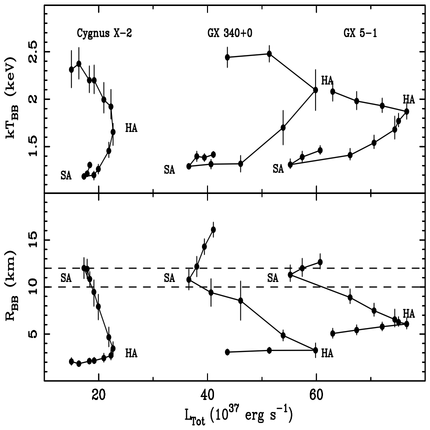

Fig. 6. Variation of the neutron star blackbody temperature along the Z-track.

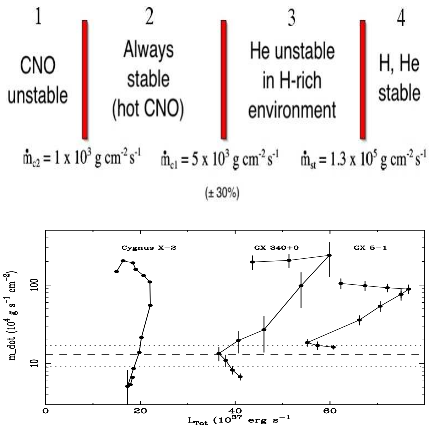

Fig. 7. Theoretical régimes of stable and unstable nuclear burning, agreeing with measured values of $\dot{m}$ (see text) at the onset of flaring.

The lack of change of $L_{\rm ADC}$ in flaring but the increase of $L_{\rm BB}$ supports the idea that $\dot{M}$ is constant in flaring but that the neutron star luminosity increases due to energy release on the surface of the neutrons star. It was found (Bałucińska-Church et al. 2010) that the onset of flaring coincides with the critical value of $\dot{m}$ ($\dot{M}$ per unit area) on the stellar surface for unstable nuclear burning (Fig. 7; Bildsten 1998). A schematic view of the physical changes taking place along the Z-track is shown in Fig. 8.

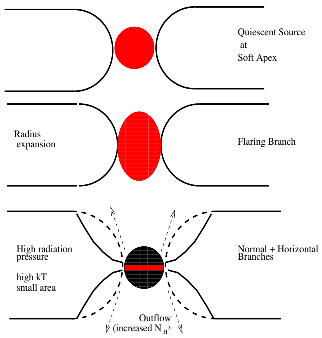

Fig. 8. Schematic view of the model of the Cygnus X-2 like Z-track sources from Church et al. (2006) and Bałucińska-Church et al. (2010).

3. Relativistic lines/reflection from the inner disk ?

A controversial question relevant to these sources, especially Cygnus X-2, relates to whether such features are seen. Done et al. (2002) proposed that Fe emission and reflection was seen in Cyg X-2. More recently, various authors have claimed the detection of relativistically broadened lines in ~10 LMXB (Cackett et al. 2010 (including Cyg X-2); Reis et al. 2009; Di Salvo et al. 2009; Shaposhnikov et al. 2009 (for Cyg X-2) in which the feature was fitted as a disk line. However, in Cyg X-2, high quality grating spectra indicate highly ionized Fe emission with Doppler broadening consistent with the outer ADC, not the inner disk and two lines are clearly resolved ~0.3 keV apart, not a Laor broadened line (Schulz et al. 2009).

4. The transient source XTE J1701-462

The outburst of this source in 2006-7 (Remillard et al. 2006) demonstrated clear changes in nature, the source moving from

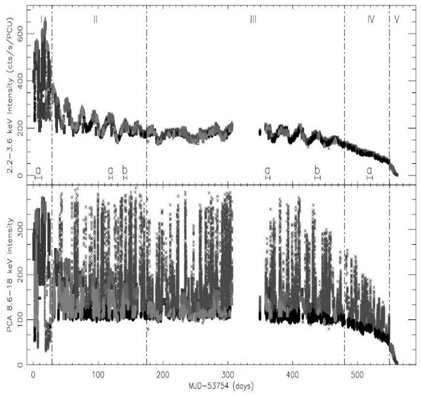

Fig. 9. Lightcurve of XTE J1701-462 from Lin et al., ApJ, 696, 1257, 2009, reproduced by permission of the authors.

Cyg-like to Sco-like and finally to Atoll like (Lin et al. 2009). It was proposed by Lin et al. that the changes were due to decreasing $\dot{M}$. However, this conflicts with the known luminosities of the classical Z-track sources in which there are no systematic differences in luminosity between the Cyg-like and Sco-like groups (see Fig. 10).

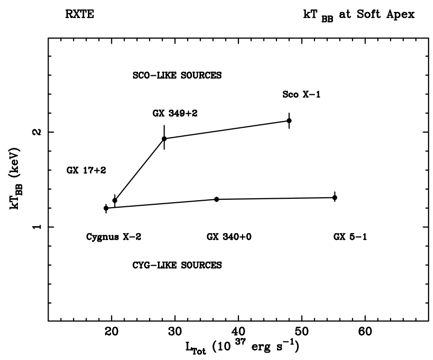

Fig. 10. Comparison of the Sco-like sources with the Cyg-like sources emphasizing a major difference: the neutron star blackbody temperature kT at the Soft Apex.

5. The Sco X-1 like sources

The main apparent differences displayed by the Sco X-1 like sources are seen in Fig. 1. Spectral fitting using high quality *RXTE* data reveals the major physical difference that at a corresponding point on the Z-track, specifically the Soft Apex, the neutron star blackbody is very much hotter (Fig. 10).

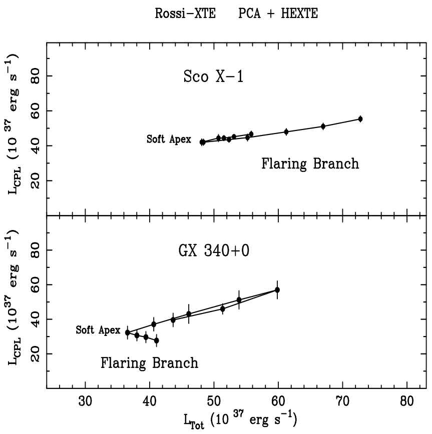

Fig. 11. Comparison of flaring in Sco X-1 and the Cyg-like source GX 340+0.

A second difference relates to the nature of flaring. In the Cyg-like sources the constancy of $\dot{M}$ was suggested by the constancy of the dominant ADC luminosity component; in the Sco-like sources L_{ADC} is not constant but increases strongly suggesting that on both NB and FB $\dot{M}$ increases.

Our recent work has investigated these effects by the use of the *RXTE* ASM over the full 15 years' life on the satellite. In Fig. 12 we compare the longterm lightcurves of the Cyg-like and the Sco-like sources. It can be seen that flaring is almost non-stop and strong in the Sco-like sources while in the Cyg-like sources it is weak and infrequent. The Sco-like source GX 17+2 appears transitional between the two groups (Figs. 10 and 12).

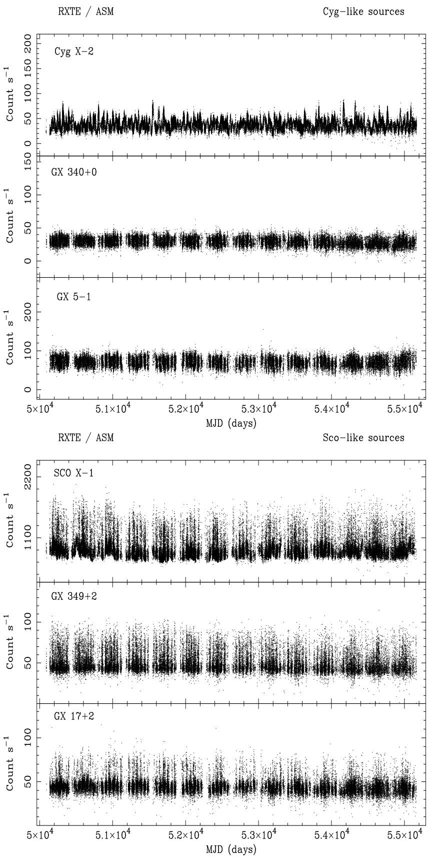

Fig. 12. The prevalence of flaring in the Sco-like sources (lower panel) compared with the Cyg-like sources (upper panel).

5.1. Model for the Sco-like sources

The almost non-stop flaring in the Sco X-1 like sources seen in the *RXTE* ASM suggests an explanation of the higher measured neutron star temperature in these sources of $kT \sim 2$ keV compared with $kT \sim 1$ keV in the Cyg-like sources. We propose that the FB consists of both unstable nuclear burning combined with increase of $\dot{M}$. The flaring clearly provides a source of heating of the neutron star and we can show that the radiative cooling time is likely to be too long to allow cooling of the neutron star. Assuming that a small fraction of the neutron star outer layers is heated, say 1%. The higher value of kT compared with the Cyg-like sources gives a stored energy of NkT where N = stellar mass/particle mass x 0.01 giving an energy of 3×10^{46} erg. If the star radiates at $L_{\rm BB} = 4 \times 10^{38}$ erg s^{-1}, the cooling time is 2 years; the 1% assumed is probably too large, but in any event the cooling time is longer than the time between flares of a few hours.

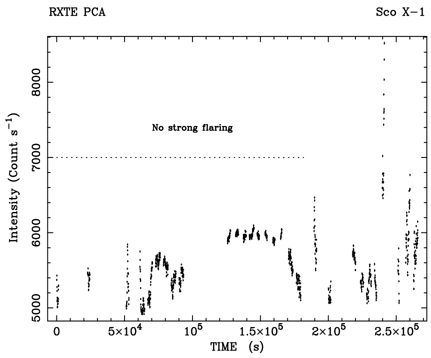

Fig. 13. Sco X-1 without flaring: *RXTE* observation of June 1999.

Testing this hypothesis is difficult given the prevalence of flaring in theses sources. However, investigation of the complete *RXTE* archive on Sco X-1 revealed a single observation in June 1999 (Fig. 13) in which there was a gap of probably 2.5 days without the normal strong flaring (allowing for data gaps). Analysis showed a small but significant reduction of neutron star temperature kT at the Soft Apex to 1.8 keV supporting the above model (Fig. 14).

We thus propose that the major differences between the Cyg-like and Sco-like sub-groups are due to the strong flaring in the latter group. Moreover, spectral studies of the Sco X-1 like group reveal that in flaring, there is both unstable nuclear burning and increase of $\dot{M}$, whereas in the Cyg-like sources flaring consists only of unstable nuclear burning. The reason for the almost non-stop flaring is not known, however, it may reflect corresponding variations in the mass flow to the neutron star.

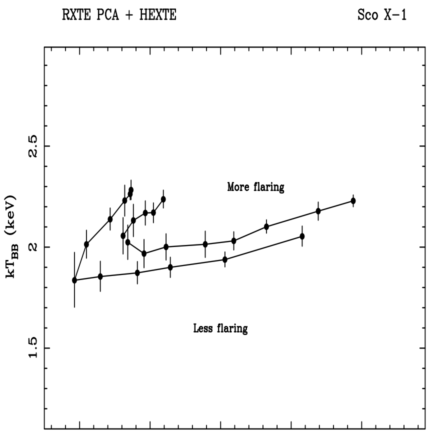

Fig. 14. Reduction of neutron star blackbody kT in the observation with reduced flaring.

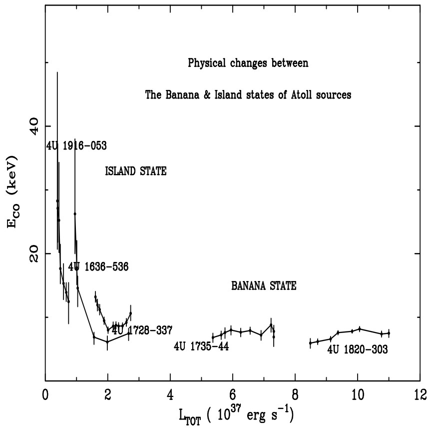

Fig. 16. The nature of the Island and Banana States: measured values of the Comptonization high energy cut-off.

6. The Atoll sources

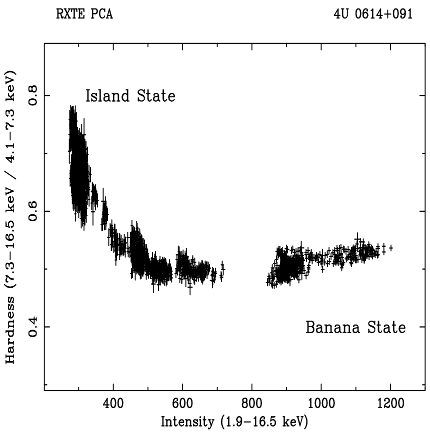

Fig. 15. Movement of a typical Atoll source 4U 0614 +091 in hardness-intensity.

Finally, the approach of spectral modelling assuming an extended ADC has also produced an explanation of the Banana and Island states in the lower luminosity Atoll sources. Fig. 15 shows a typical source in hardness-intensity in which the source moves from higher luminosity along the Banana state till at the lowest intensity the hardness increases substantially and the source moves to the Island State.

The results of our recent survey of Atoll sources reveal that the changes in hardness are essentially due to a single factor: the high energy cut-off $E_{\rm CO}$ of the Comptonized emission (Fig. 16). In brighter sources, or brighter states of the same source, $E_{\rm CO}$ is low at a few keV; however at low luminosities $E_{\rm CO}$ can rise by a factor of 10 or more. The ADC electron temperature $T_{\rm e}$ can be derived from $E_{\rm CO}$ and in Fig. 17, we compare this with the measured neutron star temperature kT. It is clear that in all sources more luminous than 2×10^{37} erg s^{-1} the ADC is maintained at a low $T_{\rm e}$ equal to kT, but for lower luminosities, $E_{\rm CO}$ and so $T_{\rm e}$ become very large due to an unknown coronal heating process.

6.1. Model for the Atoll sources

We thus propose that the Banana state consists of variations of X-ray intensity as $\dot{M}$ changes corresponding to the Normal Branch of the Z-track sources. For low $\dot{M}$ at $L < 2 \times 10^{37}$ erg s^{-1}, the cut-off energy rises to 50 keV or more because $T_{\rm e}$ rises leading to the observed strong hardness increase of the Island State.

A Flaring Branch is not possible in the Atoll sources as $\dot{M}$ is many times too small

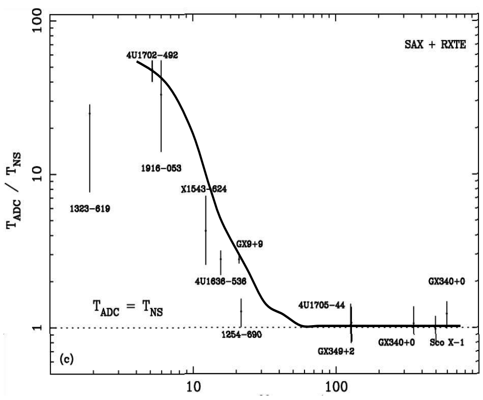

Fig. 17. LMXB survey: ratio of ADC electron temperature to neutron star temperature.

to permit unstable burning with a critical $\dot{m}$ equivalent to the high $\dot{M}$ of these sources. Thus only two tracks, not three, are seen in hardness-intensity. Of course, in the lower $\dot{m}$ régime, unstable burning of a different type: X-ray bursting, is possible.

7. Conclusions: a unified LMXB model

Based on assuming an extended ADC we find that in the Cyg-like Z-track sources the NB consists of increase of mass accretion rate (soft apex to hard apex) while flaring is unstable nuclear burning on the neutron star. In the Sco-like sources a higher neutron star temperature results from almost continuous flaring which is a combination of $\dot{M}$ increase and unstable burning. In the Atoll sources the Banana State has varying $\dot{M}$ like the Normal Branch, while the Island State is unique to Atoll sources due to a high cut-off energy resulting from heating in the corona. The Flaring Branch does not exist but is replaced by X-ray bursting.

8. Discussion

MARAT GILFANOV: The energy of hydrogen fusion is of the order of 1/30 of the gravitational energy release. Is this consistent with the average luminosity of flares ?

MICHAEL CHURCH: In the Cyg-lke sources the flare energy is consistent with unstable burning of matter accumulating on the neutron star. In the Sco-like sources it appears that flaring is a combination of $\dot{M}$ increase and unstable burning so this does not have to supply all of the increased luminosity.

THOMAS BOLLER: You said that the unstable burning is related to an increased accretion rate. Are the processes physically connected ?

MICHAEL CHURCH: It is not clear what causes non-stop flaring in the Sco-like sources, or whether burning is triggered by accretion variations or by other changes such as in emitting area on the neutron star.

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