Black Holes from Stars to Galaxies – Across the Range of Masses
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SS433 and the nature of ultra-luminous X-ray sources

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Abstract. The prototypical micro-quasar, SS433, one of the most bizarre objects in the Galaxy, is a weak X-ray source, yet the kinetic energy of its relativistic, precessing jets is vastly greater. In spite of its importance as the nearest example of directly observable relativistic phenomena, we know remarkably little about the nature of this binary system. There are ongoing arguments not only about the mass of the compact object, but even as to whether it is a black hole or a neutron star, an argument that recent high resolution optical spectroscopy has contributed to.

Combined with the INTEGRAL discovery of a new class of highly obscured galactic high-mass X-ray binaries, one of which has been found to precess on a similar timescale to SS433, we suggest that these would indeed be seen by external observers as ULXs, once additional effects such as beaming (either relativistic or geometrical) are included.

Keywords. Accretion, accretion disks – black hole physics – X-rays: binaries

1. Introduction

Over the last 25 years SS433 has become one of the most well-known and yet most enigmatic objects in the Galaxy. In spite of intensive studies at all wavelengths, some of its key features are little understood, there even remains controversy over the nature of the compact object. Yet SS433 is extremely important as the first relativistic jet source discovered in the Galaxy, and only continuously emitting micro-quasar. Its key property is the 162d precession period in the *moving* emission lines associated with the 0.27c jets which are ejected in opposite directions from the compact object (Margon 1984). Whilst their properties are well described by the Kinematic Model (Margon 1984; Fabrika 2004), the jet kinetic energy exceeds 10^{40} erg s^{-1}, and yet the observed X-ray flux (from A1909+04) is only $\sim 10^{36}$ erg s^{-1} (for its assumed 5.5kpc distance, Blundell *et al.* 2004). This has been explained by the presence of both optical and X-ray eclipses, indicating a high binary inclination (79°, Margon & Anderson 1989) and hence that SS433 may be an Accretion Disc Corona (ADC) source in which we only see a small fraction of the intrinsic X-ray flux which is scattered into our line-of-sight. If true, this would imply that the intrinsic L_X is indeed much greater, and that if observed at a lower inclination SS433 would be one of the most luminous objects in the Galaxy. Based on the jet kinetic energy, presumably powered by accretion, SS433 may well provide a link with the ultra-luminous X-ray (ULX) sources, whose luminosities require compact object masses $>10M_\odot$ if they are Eddington limited (e.g. Fabbiano 2004).

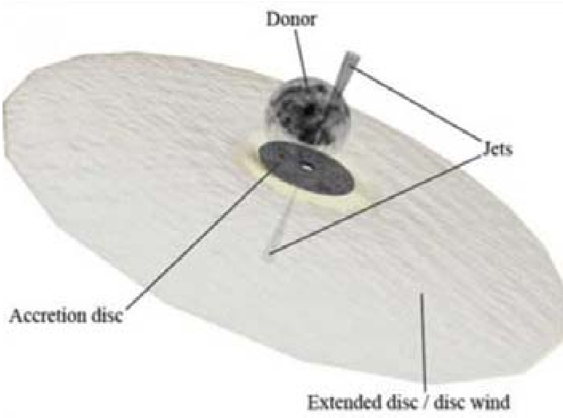

Figure 1. Schematic diagram of the SS433 system with a simplified portrayal of the impact an extended disc might have on the visibility of different components (from Barnes *et al.* 2006).

The eclipses occur on a 13d period, and modelling of INTEGRAL light-curves (Cherepashchuk *et al.* 2005) gives a mass ratio, $q(= M_X/M_2)$ ~0.2, implying that the mass donor is a large, early-type (~B) star and hence that SS433 is a high-mass X-ray binary (HMXB) with an extremely high mass transfer rate ($\sim 10^{-4} M_\odot yr^{-1}$, King *et al.* 2000). This is confirmed by optical spectra, which exhibit powerful P Cyg profiles in the "stationary" (presumably disc-based) lines of H, He (see e.g. Barnes *et al.* 2006), which are similar to those seen in Wolf-Rayet spectra with comparable mass-loss rates. Indeed ISO spectra (Fuchs *et al.* 2006) of SS433 have been compared with WN8 stars, and indicates that we are observing a dense outflow at the centre of which is embedded an ionising source, and it matters little whether this is driven by a very hot star or accretion onto a compact object. The eclipses establish 13d as P_{orb}, and hence the 162d precessional period is one of the *superorbital* periods seen in ~20 X-ray binaries (see e.g. Clarkson *et al.* 2003). Such behaviour makes SS433 an ideal laboratory for studying precessional disc properties, producing insights relevant in a wide variety of scenarios such as AGN, young stellar objects and galactic discs.

Crucially there is also a diffuse radio component that has been observed *perpendicular* to the main jets (Blundell *et al.* 2001) which is interpreted as an equatorial outflow from the accretion disc, occurring as a result of the extremely high $\dot{M}$(see fig 1).

In spite of our knowledge of its binary orbit, SS433 is currently absent from the list of dynamically determined compact object masses (Casares, these proceedings). This is because it is well-known (e.g. Crampton & Hutchings 1981) that the donor's spectral type is poorly determined (a combination of high reddening and strong, broad disc lines that mask the principal stellar absorption features), and so previous mass determinations have been obtained from emission line radial velocity curves. These range from $M_X = 0.8$–$62 M_\odot$ (d'Odorico *et al.* 1991; Antokhina & Cherepashchuk 1985), thereby leaving the nature of the compact object completely indeterminate, a most regrettable situation for such an important system.

This is the first of two related papers on SS433 (see Fabrika, these proceedings), addressing recent observational and theoretical results that have attempted to provide better constraints on its fundamental parameters.

2. Direct observation of the donor?

The holy grail in making further progress clearly resides with the direct detection of the donor, ideally through stellar absorption features, or possibly via the recently developed technique of Bowen fluorescence emission from the donor's X-ray irradiated

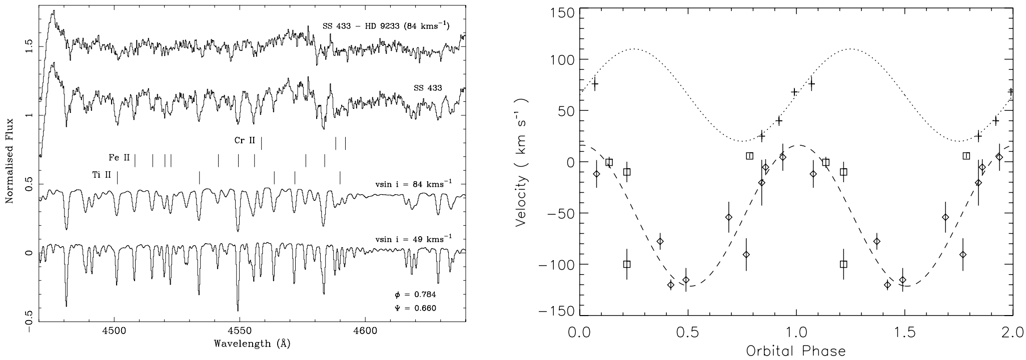

Figure 2. Left: WHT spectrum of SS433 obtained on 2004 June 29 at (Ψ, ϕ=0.66,0.78) together with the A4Iab standard HD9233 (below) shown broadened by different amounts. The top spectrum shows the SS433 residuals after subtracting the optimally broadened spectrum of HD9233. Right: Radial velocities from our SS433 campaign (squares are spectra discussed in the text) and best-fitting RV curve (dashed line; the upper dotted RV curve and velocities, pluses, are from Hillwig *et al.* 2004).

atmosphere (see Casares, these proceedings). However, the absence of any sharp features in the $\lambda\lambda$4640-50 blend precludes the latter approach. Furthermore, most previous spectroscopic studies of SS433 have concentrated on low resolution in the visual/red region (where SS433 is much brighter) so as to monitor the longer term behaviour of the jets using small telescopes. However, if the donor is an early-type star then the best spectral features are in the blue (λ <4800Å), but the combination of SS433's reddening ($A_V \sim$8) and the weakness of the features requires the use of large telescopes.

Several groups have attempted such studies, with apparently positive results. Gies *et al.* (2002) claimed the detection of A7I features during optical eclipse and at precessional phase $\Psi \sim$0 (i.e. disc open, which is why these features were only detected during eclipse). Their reason for observing at such Ψ was their assumption that the extended equatorial disc (fig 1) would otherwise obscure the photosphere of the donor, and that it needed to be observed "above" this disc. However, with velocity points only around orbital phase $\phi \sim$0, the sampling of the radial velocity (RV) curve is poor. Nevertheless, by combining these with the archival HeII emission line RV curve (Fabrika & Bychkova 1990), masses of 19 ± 7, $11 \pm 5 M_\odot$ were derived for M_2, M_X (Gies *et al.* 2002), with $M_2 > M_X$ as expected for very high $\dot{M}$(King *et al.* 2000). However, further observations (Hillwig *et al.* 2004) which included a reanalysis of the earlier data led to a compact object mass M_X of only $2.9 M_\odot$. This large uncertainty in M_X is inevitable when the RV curve amplitude, K_2, is poorly constrained, as this translates directly into very large uncertainties in the mass function $f(M) = PK_2^3/2\pi G$.

What is needed is high S/N, intermediate resolution blue spectra over a wide range of Ψ and ϕ, which we obtained using various telescopes and instruments, but mainly the 4.2m William Herschel Telescope on La Palma equipped with the ISIS spectrograph (see Barnes *et al.* 2006). In contrast to Gies *et al.*, we elected to concentrate on $\Psi \sim$0.3–0.7, when the disc would be closest to edge-on, as SS433 is then $\sim$0.5mag fainter (Fabrika & Irsmambetova 2002), and hence the disc contamination is reduced. This approach appeared to be vindicated when we obtained the spectrum shown in fig 2 at (Ψ, ϕ=0.66,0.78), an excellent match to a "normal" A4Iab stellar spectrum, and where most of the weak absorption features present are due to FeII. Interestingly the phasing of this spectrum is at a time when the donor is mostly *below* the extended disc outflow of fig 1.

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Furthermore, by broadening the template star HD9233 spectrum, subtracting it from our SS433 spectrum and χ^2-testing the residuals we were able to determine the rotational velocity to be 84±5 km s^{-1}(Barnes *et al.* 2006). However, the main reason for obtaining such spectra was to attempt to construct a RV curve from these "normal" spectral components, and this is shown in fig 3, together with the results of Hillwig *et al.* (2004) for comparison.

While an (approximately) sinusoidal modulation appears to be present, it is clearly at the wrong phase to be associated with the donor (X-ray/optical eclipse is at phase 0), and is offset in systemic velocity, γ, with respect to the compact object (based on the HeII RV curve, Fabrika & Bychkova 1990). This is also true for the Hillwig *et al.* RV points (upper curve in fig 3), and interestingly one of our spectra is not far removed from those points. However, we have strong evidence that the absorption features of fig 2 do *not* arise on the donor, in that (a) at (Ψ, ϕ=0.14,0.85) they are measured to be significantly *narrower* than in fig 2 (and hence the broadening measured is *not* due to the rotation of the donor, and (b) at (Ψ, ϕ=0.22,0.86) the features are *doubled*. Hence there are sites within SS433 that can clearly mimic the spectrum of a ∼mid-A supergiant, but that are not physically associated with the mass donor.

Additional observations of SS433 (Cherepashchuk *et al.* 2005) also find cooler spectral features during eclipse, but their ∼3Å resolution spectra give K_2=132 km s^{-1} which, when combined with the same HeII K_X, yields a q which is incompatible with the observed X-ray eclipse, and masses of M_X, M_2 = 62, 206$M_\odot$! Consequently they used irradiation effects to reduce K_2 to 85 km s^{-1}(which is then compatible with the q of 0.3 inferred from the X-ray eclipse), and gives M_X, M_2=17, 55$M_\odot$, although the effect of heating by the jets can reduce K_2 further to 70 km s^{-1}and the masses to M_X, M_2=9, 30$M_\odot$ (which is then in line with the black hole masses presented by Casares). However, it may simply be that these features are not clear indicators of the donor properties or even associated with the donor at all, as indicated by our higher resolution spectra above, and which would explain the difficulty in obtaining sensible mass constraints.

3. Implications for SS433

Our spectra raise uncertainties as to whether the mass donor has been identified at all. Furthermore there is now substantial observational evidence (e.g. Clark *et al.* 2006) for the presence of powerful outflows, possibly an extreme disc wind, which may well be the source of the ∼10^{4}K gas identified in our spectra. Hence they are of limited use in dynamical studies.

Such outflows require very large $\dot{M}$ from the donor, and hence an extremely high L_X, but observing this would depend very much on the viewing angle, i.e. there will be beaming, which may be a significant effect in the extragalactic ULX sources (King *et al.* 2001). However, at higher X-ray energies and γ-rays, it is possible for these objects to be seen even through high column densities of material, and so SS433 may also be related to the recently discovered class of highly obscured INTEGRAL sources (Revnivtsev *et al.* 2003). Interestingly, one of these, XTE J1716-389, has been found to exhibit a 99d modulation (Cornelisse *et al.* 2006).

Are there other sources in the Galaxy which may be related to SS433 and the ULXs? Perhaps the best candidate is GRS 1915+105, which is both a luminous X-ray source and a micro-quasar (see Casares, these proceedings). Indeed, while peaking at L_X ∼10^{39} erg s^{-1}, when corrected for the absorbing column this value could be 10 or even 100 times greater (Greiner *et al.* 1998). And many of the X-ray transients show relativistic jet ejections and extremely high, but non-steady, X-ray fluxes (McClintock & Remillard

2006, Fender 2006). However, it must also be noted that there are at least two well-known sources, A0538-66 (Charles *et al.* 1983) and Cir X-1 (Saz Parkinson *et al.* 2003), which have X-ray fluxes $>10^{38}$ erg s^{-1} and are clearly identified as neutron star systems, on the basis of pulsations and bursts respectively.

4. Conclusions

(*a*) determining the component masses of SS433 is extremely important, both for understanding the late stages of evolution of massive stars and the nature of ULXs, but the current observations are able to provide little in the way of sensible constraints;

(*b*) we have detected normal, early-type stellar absorption features, but their behaviour (variable $v\sin i$, line doubling, RV phasing, γvelocity) excludes them being associated with the donor star;

(*c*) the spectroscopic data are consistent with the presence of large mass outflows, possibly a form of extreme disc wind, as expected if $M_2 > M_X$ and SS433 is a HMXB with a black hole compact object;

(*d*) to make further progress in understanding SS433 we need more systematic coverage of *all* orbital and precessional phases with high resolution, high S/N blue spectroscopy. This is difficult with classically scheduled telescopes, but is ideal for Q-scheduled telescopes such as SALT;

(*e*) SS433 would likely be classed as a ULX if it were being observed closer to the jet axis, i.e. a result of the highly non-isotropic pattern of its radiation, which could be due to either relativistic beaming or a more simple geometric effect due to an extremely thick disc which obscures the X-rays except when viewing perpendicular to the disc. Interestingly, if this were true it implies that ULXs in external galaxies should be examined for regular X-ray variability on long timescales comparable to those of the SS433 precession period where the motion of the jet across the line-of-sight would produce a large modulation in the flux;

(*f*) it should nevertheless be noted that other candidates for galactic ULXs include at least two known neutron star systems, A0538-66 and Cir X-1;

(*g*) there are other black-hole candidates, such as the recently discovered INTEGRAL class of highly-obscured HMXBs, that may also be related to SS433.

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Fukun Liu: In the classical scenario for SS433, the accretion disc is flat but with an inclination angle with respect to the binary orbital plane, while in the configuration presented by Andrew King the accretion disc is warped. If we observe emission lines from accretion disc surface, the emission line profile in the latter configuration should be asymmetric and change periodically. Have you observed such signature?

Phil Charles: The broad H_α emission line of SS433 is very complex. We should refer this question to Andrew King to ask him whether we could observe it; I doubt it is possible...

Felix Mirabel: Is the absence of an IMBH/ULX sources in our Galaxy consistent with the statistics on ULXs in nearby galaxies? Other way to put the question, why there is no IMBH in the Milky Way ULXs?

Phil Charles: There are luminous X-ray sources in the Milky Way (e.g. GRS 1915+105, A0538–66) which might be viewed externally as ULXs, but we know that both are consistent with $M_X \sim 14 M_\odot$ (GRS 1915+105) and $\sim 1.5 M_\odot$ (A0538–66) based on dynamical information. This suggests that IMBH interpretations of ULXs have to be treated with caution.

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