solar activity. I assume it is small.

Professor Robinson. The one important thing to know about non-linear processes is that correlation becomes less clear cut. If you correlate stimulus and response for linear processes you get a good correlation. The problem with non-linear processes is sometimes it happens when a stimulus is present and sometimes not, because of the critical conditions you need as well. It is certainly true that a number of types of aurorae are associated with things like sub-storms, which give rise to the conditions I have mentioned.

Professor S. J. Schwartz. Isn’t it the corollary that all electrons in the outer magnetosphere come from this region as well?

Professor Robinson. It is possible, because this process produces upward-going electrons too, so it is feeding energetic electrons into the magnetosphere. I haven’t thought about the consequences of that, but it is interesting, and is the very mechanism we are hoping to check out with the Cluster spacecraft: from their location, the only effect of this process which they are likely to see is these electrons shooting out from the acceleration region along the field lines. This is an interesting speculation and I don’t know the answer yet.

Mr. H. Regnart. Have you thought about the application of this model to other planets and atmospheres?

Professor Robinson. I haven’t; but I would say it is obvious that it must work anywhere, if physics is physics and as long as there is a source of Alfvén waves, field lines, and an ionosphere whose density falls off with height. If Chapman is right, and Alfvén is right, it should work.

[A vote of thanks to Professor Robinson was given by Dr. Betty Lanchester for his 1999 Jeffreys lecture.]

The President. May I thank all our speakers again. The meeting will now close, and drinks will be served outside.

SUMMARY OF THE RAS DISCUSSION MEETING ON

MICROQUASARS

The half-day discussion meeting on ‘Microquasars’ was held at the Scientific Societies’ Lecture Theatre, Savile Row, London, on 2001 May 11.

The meeting began with a talk from Rob Hynes (Southampton) entitled ‘HST observations of microquasars and related X-ray binaries’. He explained that he and his many collaborators have used several telescopes including RXTE, UKIRT, AAT, WHT, etc., mostly through target-of-opportunity programmes. The HST is particularly useful for observations of microquasars and related objects for several reasons. First, it covers a very wide wavelength range, from 1150–10300Å. This allows UV observations to be made which would be impossible from the ground, and also enables the evolution of the spectral energy distribution (SED) to be followed. The access to UV wavelengths also allows the observation of high-ionization lines (C iv, N v, etc.), which trace the disc wind and allow the observer to probe abundances in the accreting material, thereby enabling the study of the evolutionary history of the binary system. Finally, the excellent time resolution (125 μs on individual photons), when combined with RXTE observations, enables ‘echo mapping’ of the system.
Turning to the results of observations, Dr. Hynes emphasised that studies of soft X-ray transients (SXRTs, also known as X-ray novae) and black-hole X-ray transients (BHXTs) can help us to understand microquasars, and to this end he described multi-wavelength observations of Nova Muscae made in 1991, GRO J0422+32 (1994), GRO J1655−40 (1996), XTE J1859+226 (1999/2000), and XTE J1118+480 (2000). The SEDs for these types of object are expected to show some combination of three basic features. Firstly, one expects to see the disc, with a spectrum that depends on whether it has been viscously heated or heated by X-rays, in which case the spectral peak would be in the near-UV. Secondly, the heated companion star should be seen, showing a thermal peak in the optical/UV, and thirdly one may expect to see the jet, perhaps emitting synchrotron radiation.

Nova Muscae showed a spectrum which was reasonably well-described by a viscously-heated disc alone. The lack of other features in the spectrum is probably because it was observed late in an outburst phase.

GRO J1655−40, the ‘classical’ microquasar, was found to display a spectrum that did not follow either the viscous or the X-ray-heated models. There was a strong optical peak, which may be caused by the secondary star, as it is quite large in this system. However, it is less clear why the spectrum observed is so flat. This would require accretion close to the Eddington limit, which is not borne out by the X-ray emission. During the observations, the optical emission was seen to fall in intensity while the X-ray and gamma-ray emission increased. This is difficult to interpret, and may be due to warping in the accretion disc.

Conversely, the spectrum of XTE J1859+226 is rather easier to interpret. The earlier observations are fitted well by an irradiated-disc model, and when the object is fainter the spectrum fits a viscously-heated-disc model. The IR observations for this object were particularly important in showing the black-body fall-off of the spectrum.

XTE J1118+480 shows a flat spectrum from IR to UV. This is hard to interpret as disc emission, in which case one would expect to see a fall-off in the IR emission. The most likely interpretation is that the black-body emission is swamped by synchrotron emission. The Balmer jump that is observed may be a viscously heated component.

With the aid of a fish, Dr. Hynes went on to describe the technique of ‘echo-mapping’, which is not unlike sonar. We expect to view X-rays from the source and reprocessed optical emission caused by X-rays impinging on the inner face of the disc or the secondary star. By measuring the delays between the X-ray and optical emission, path lengths between the X-ray source and the target material can be measured, thereby providing a method of ‘mapping’ the system. The first time this technique was tried, on GRO J1655−40, the measurements were somewhat hampered by noise, but assuming a simple Gaussian transfer function gives time lags between the X-rays and the reprocessed emission in the range 10–20 seconds. From what we know of the system at phase 0.38, which is when the observations were made, we would expect the lag for reprocessed emission from the secondary to be 40–60 seconds, suggesting that the emission observed was coming from the accretion disc. Rather better observations of XTE J1118+480 revealed large-amplitude variability on short timescales, which is very useful for echo mapping, enabling the derivation of a model-independent transfer function. Longer-wavelength reprocessed radiation was seen to be more delayed than the shorter-wavelength emission, the first time such wavelength-dependent time lags have been seen. The secondary star was again not
seen, and the time lags observed are consistent with emission from the accretion disc, but the responses are surprisingly sharp. It was suggested that there may be a mistake in the timing, or that there is something missing in the interpretation of the emission — perhaps we are seeing the jet?

Dr. Hynes summed up his talk by saying that the optical emission from these systems does appear to be consistent with it being reprocessed X-rays, and some SEDs at least suggest that the emission is primarily from the accretion disc. However, this interpretation begs some questions: for instance, why the X-ray and optical emission are not always well-correlated and why in the XTE J1118+480 system the X-rays and UV emission are correlated even when it is in a low state, when very little X-ray emission would be expected.

The next talk was about the coupling of accretion and ejection in X-ray binaries (XRBs), and was given by Rob Fender from the University of Amsterdam. His fundamental question was: how common are jets in X-ray binary systems? The thrust of his talk was to demonstrate that they are, in fact, quite common. The jet in an XRB is usually revealed by its synchrotron emission, which most probably produces radio emission, though it is not clear that there is an upper limit to the energy of its emission. Considering the classes of XRBs, of the 80 high-magnetic-field neutron-star systems that have been studied, none shows synchrotron emission. The low-magnetic-field neutron-star XRBs divide into two types, the Z-sources and the atoll sources. Of the Z-sources, all show radio emission and one (Sco X-1) is known to display jets, whilst of the 120 atoll sources studied, only five show radio emission. In the case of the persistent black-hole sources, all four show radio emission, and three of the four are known to have jets. The 16 transient black-hole systems that have been studied are almost all radio sources (only one is not) and six are observed to contain jets. Dr. Fender suggested that, in fact, all the atoll systems should display jets, but they are weak emitters.

Dr. Fender went on to consider the accretion states of the black-hole systems. Referring to the X-ray emission properties, there are four of these: the low/hard state, the intermediate state, the high/soft state, and the very-high state, which are believed to relate to different relative sizes between accretion discs and haloes. It is in the low/hard state that the radio emission reveals a steady self-absorbed jet, examples being Cygnus X-1 and XTE J1118+480.

The key to the existence or otherwise of jets in the other types of source appears to lie in the magnitude of the neutron star’s magnetic field. The atoll and Z-sources have B-fields of typically $10^8$ and $10^{10}$ gauss respectively. The X-ray pulsars have magnetic fields of $10^{12}$ gauss, which for some reason is too high for the formation of jets. The radio emission is strongest in the Z-sources when the mass-transfer rate is lowest. Radio emission from the atoll sources is more elusive. A study of 1728 – 34 has shown a lower X-ray flux than would be typical of a Z-source, indicative of the lower mass-accretion rate. Radio observations of the object give a detection four times out of six, but at the sub-milliJansky level. This suggests that many more pointed observations of the atoll sources are needed to establish whether jets occur in them.

In the X-ray transient sources, of which GRS 1915+105 is a classic example, X-ray outbursts correspond to increased accretion and jet formation. After outburst, most XRTs go into a high/soft state and fade, but some go into a low/hard state showing a powerful jet. The correlation between radio and X-ray emission in these sources implies coupled accretion and outflow during outburst.
There is only a hint of the correlated X-ray/radio behaviour in neutron-star systems, and the ratio of radio to X-ray flux (radio loudness) is greater for black holes than for neutron-star systems. The question is whether this is indicative that neutron stars are ‘radio quiet’ or ‘X-ray loud’. Maybe black holes are more efficient at producing jets due to their greater gravitational potential or maybe they produce fewer X-rays due to matter crossing the event horizon, or possibly there is some combination of these effects. This is an area which requires further research.

Ralph Spencer (Jodrell Bank) picked up the theme by considering radio jets in X-ray binaries. He started with some examples of observations.

SS433, observed in 1987 May, shows apparently smooth jets on the arcsecond scale, but we also see discrete ejection in the inner core. EVN/MERLIN combined observations clearly show discrete knots of emission, and the overall jet structure is S-shaped.

MERLIN observations of GRS1915+105 show a pair of ejection events with a follow-up ejection event. There was also an outburst observed during the UK’s recent foot-and-mouth outbreak (the two events are not thought to be causally related), which was on the whole a one-sided ejection event. The object also shows a persistent mini-jet in the low state that appears to be double-sided.

VLBA 8-4-GHz observations of Cygnus X-1 made in 1998 August show clear evidence of a jet, possibly exhibiting a ‘kink’, not apparently a blob of matter that has moved along the jet. However, if motion in the jet were relativistic, then we would expect to see 110-mas/day motion, in which case the jet could be smeared out in observations and there may be discrete blobs of matter after all. In this case one would also expect to see high emission from side-lobes, which are not detected.

Dr. Spencer presented several questions that require answers. Are the bright knots observed in jets really blobs of matter in the jets or are they enhancements in the general background? Are the low-power jets really continuous? Do changes in the inner disc or coronal region cause a transient change in jet velocity?

A ‘shock in jet’ model can easily explain the bright knots in jets as regions of compression. It would make the jets in microquasars very similar to the jets observed in extragalactic sources, and the acceleration of particles in shocks is a convenient source of relativistic electrons, which can then be responsible for the synchrotron radiation. The quasi-steady production of a continuous jet would also be consistent with continuous accretion. However, there are problems with this model. One would expect to observe varying knot velocities as conditions change — in the case of SS433, the velocities of the knots are stable to within a few percent. Kelvin-Helmholtz instabilities should also be seen, but are not. In addition, at least for the radio emission, the re-acceleration of electrons in jets is not required as the radiative lifetimes for synchrotron electrons are much greater than the lifetime of the sources (i.e., years and not days).

Despite these difficulties, the observations do seem to favour the existence of blobs in microquasar jets. Continuous jets appear to exist on the tens-of-AU scale, and energy considerations favour positron-electron jets. Some further tests are required, including high-dynamic-range observations and polarization measurements (one expects to see the magnetic field perpendicular to the jet in a shock). Circular-polarization measurements may settle the question of the composition of the jets. Observations of Cygnus X-1 to be made on 2001
May 31 with MERLIN are expected to test whether the jets of tens of AU are really smeared out.

The next speaker, Sylvain Chaty (Open University), considered IR emission from microquasars, which is expected to be produced by the jets and also by dust around the system.

The first object considered was XTE J1859+226. The RXTE observations of this object in outburst show a fast rise and exponential decay, which is not observed in the radio waveband, where the emission is clearly synchrotron in origin. The X-ray and IR emission show a similar time spectrum, which suggests that the IR emission results from reprocessed X-rays. Data taken with the Nordic Optical Telescope when the object was in the high and less-active states shows a 24-minute periodicity, and it has been speculated that this is caused by accreted matter at the Lagrangian point. However, the periodicity has not been confirmed in later observations. The SED observed with HST and UKIRT is well-fitted by either a simple X-ray-heated-disc model or a viscous disc, as noted by Rob Fender. The synchrotron radio emission could extend to the IR, so it is possible that some of the IR emission is non-thermal.

XTE J1118+480 is a particularly interesting object, as it has a very flat X-ray light curve. The IR light curve decreases before reaching the optical region, and the radio emission is also quite flat. IR observations in the K-band show variability of up to 0.8 magnitudes, the first time such strong variability has been seen in an object of this type. This variation is mirrored by optical emission. This again suggests a non-thermal origin for at least some of the IR emission. The IR spectrum also looks as though it is a continuation of the radio emission, which would explain the featureless IR spectrum observed during outburst.

The observations described above support the existence of IR emission from jets in these objects. The next question Dr. Chaty addressed was that of emission from dust surrounding microquasars. SS433 is the best-known example of the interaction of jets and dust. However, there may be others. A particularly good candidate is GRS 1915+105. The ejection event in 1995 showed an increase in IR emission 2–5 days after the radio event. This can be interpreted as being due to heated dust in the environment of the source, with a likely temperature of about 2300K, but it is also possible that it is due to synchrotron emission from the source itself. It has been suggested that GRS 1915+105 may be a 'relativistic Herbig-Haro object', with discontinuous matter ejection. This marks the main difference between GRS 1915+105 (and also GRO J1655–40) and SS433 — the jets in GRS 1915+105 are faster but more sporadic.

A large, rapid flare has also been seen from V4641 Sgr. During the outburst, the optical colour did not change, but there was a 0.9-mag. change in infrared (F − K) colour, which could perhaps be interpreted as indicative of jet/dust interaction.

In summary, we see infrared emission from the jets in GRS 1915+105, XTE J1859+226, and XTE J1118+480. It is likely that we are seeing infrared emission from dust in GRS 1915+105, V4641 Sgr, and SS433, although only in the last of these is the evidence conclusive. The answer, of course, is more observations.

Andy Fabian (Cambridge) spoke about X-ray emission from microquasars. The goal of observations of these objects is to understand both accretion and jetted outflows, particularly the innermost flows around black holes. In this, X-rays are critical, not least because most of these objects are discovered via their X-ray emission. X-ray observations can provide both spectra and timing information. We need to try and generalize from the observations we have at present.
The quasi-black-body emission seen from the disc is often used to deduce the inner radius of the disc, using multi-colour disc models. However, the outer layers of the hottest part of the disc are not optically thick to the highest-frequency radiation. Detailed modelling of the density and temperature profiles in the outer few Thomson depths of the disc is required. The radius may appear to change even when it is actually fixed, purely by changing its density structure. There are also now new ingredients, specifically the warm absorber in XTE J1118+480. The observations of XTE J1118+480 are interpreted as giving the inner radius of the accretion disc at several tens of Schwarzschild radii, but the spectrum is not a power law, hence the requirement for a warm absorber, something which is commonly invoked in models of AGNs. If the inner disc radius is so big, this suggests an advection-dominated accretion flow (ADAF) in the inner region. However, if there is a cloud of material in the system, and if there is a carbon edge, we should also see lots of He absorption, which we do not.

Another use of X-ray observations is to look for reflection signatures. Direct emission will be a power law, and the reflected continuum will be quite weak in comparison. That said, it is expected that there will be a strong Fe fluorescence line observed. Professor Fabian described some of his models, which can produce lots of complex spectra, and may be able to tell us something about the material around the X-ray source. Crucially important are surface effects — if accretion discs are highly ionized they will act like mirrors. We can also try to learn something from radio galaxies. All observations of these indicate the reflection signature is weak in nearby radio galaxies (e.g., 3C111, 3C120, 3C82, etc.) if it exists at all. We cannot really rule out any geometries at all for microquasars. ADAF, a Thomson thick corona, the corona in mild bulk relativistic motion — all these things can be invoked to reduce reflection; perhaps a combination of these effects applies.

X-ray timing measurements can possibly measure black-hole spin. GRO J1655-40 has 450-Hz quasi-periodic oscillations (QPOs). If these are caused by Keplerian motion, we would need a spinning black hole of mass \(5 \cdot 5-7 \cdot 9\) \(M_\odot\); but it is not clear what causes QPOs. It is possible that the differences we see in the characteristics of AGNs and microquasars are related to the relative importance of black-hole spin in the two types of systems — perhaps spin is always lower in AGN black holes.

Professor Fabian then considered some specific observations. GRS 1915+105 was observed with Chandra during outburst to measure its X-ray spectra. The observations showed evidence for neutral and ionized edges, including neutral Fe K-edge emission, and Fe XXV and Fe XXVI absorption. Unfortunately, the observations had been difficult to make due to telemetry and pile-up problems.

A further question to consider is that of extragalactic microquasars. How many might we expect to see? Many galaxies have off-nucleus X-ray sources with \(L_X > 10^{39}\) erg s\(^{-1}\), M82 for instance. This would suggest a typical black-hole mass of 10–100 \(M_\odot\), but a luminosity of \(10^{41}\) erg s\(^{-1}\), which is sometimes observed, would suggest a black-hole mass of as much as \(1000\) \(M_\odot\). In the case of M82, Professor Fabian favours a compact supernova remnant as the off-nucleus X-ray source, but one can speculate whether it is a microquasar beamed along our line of sight (a microblazar?). A jet speed of 0.9c gives a Lorentz factor, \(\gamma\), of 3, and this then beams into \(\gamma^{-2} \gg \alpha 1\) sr. If there are ten microquasars in each galaxy, then we would probably expect to see about one microquasar beamed towards us per five galaxies.
In summary, X-ray observations offer the potential to see inside the ‘black box’ of accretion into jets — but it is early days yet.

The final speaker was Felix Aharonian (MPIK, Heidelberg). He addressed the question of gamma-ray emission from microquasars. We know that several AGNs are gamma-ray sources, some emitting strongly in the very-high-energy (VHE) gamma-ray region, which runs from about 50 GeV to several TeV. It seems logical to suggest that at least some microquasars will also be producers of GeV and TeV gamma rays. Similarities between the two classes of object include the existence of non-thermal (synchrotron) radiation up to the near-IR region and magnetic fields of approximately 0.1 gauss, which suggests the presence of electrons with energies up to about 1 GeV. The hard X-ray flux also strongly suggests the presence of non-thermal photons. Gamma rays are expected to be produced by the inverse Compton process on the ambient photon fields. The main differences between the two classes of object are that there is no significant $\gamma-\gamma$ absorption problem for gamma rays from the much closer microquasars, and also that the Doppler factors are likely to be smaller for microquasars. From the point of view of gamma-ray observations, especially in the TeV region, the former is an advantage, the latter a disadvantage, though it should be said that the microquasars do appear to be very powerful.

Simple arguments suggest that the typical gamma-ray flux from microquasars should be around $10^{-12} - 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, detectable with GLAST and also with ground-based telescopes.

What could gamma-ray emission tell us? Primarily, gamma-ray emission can tell us about the non-thermal energy budget of these objects. Gamma-ray observations are also capable of providing a measure of the B field in the object, and this is of course important for jet theory. The maximum energy of photons observed will also provide a measure of the acceleration rate and hence provide information about the acceleration mechanisms operating in these objects. Again, a simple model suggests that a typical maximum energy could be around 17 TeV. Gamma-ray observations can also tell us the nature of the accelerated particles: protons or electrons.

GRS 1915+105 is a good object to model, because we know a lot about it. Using the information available, it is possible to model 1–10 GeV electrons. To model TeV gamma rays, we would need to assume that the electron spectrum continues, but this would depend on the B field and the electron cut-off. Calculations of the time evolution of the fluxes of synchrotron and inverse-Compton gamma rays from GRS 1915+105 for a strong flare similar to the famous 1994 March/April event suggest that fluxes of $\gamma$-rays above several 100 GeV could be as strong as the Crab flux.

The prospect of the existence of microblazars is very exciting, especially since all the AGNs so far detected at TeV energies are blazars. Here, it is possible to assume a higher Doppler factor for the jet. The spectrum of SS433 fits a synchrotron spectrum very well, and is similar to that of the VHE gamma-ray-emitting blazars. The inverse Compton emission, which is assumed to give rise to the gamma rays, is very sensitive to the B field in the system, with a higher magnetic field giving rise to a lower VHE $\gamma$-ray flux. Observations of SS433 made with the HEGRA telescopes suggest that the B field > 10 $\mu$G. HESS and VERITAS will be able to probe to 30 $\mu$G.

It is possible that persistent emission was seen with EGRET from LS 5039, as this object is in the 95% confidence-limit contour. This could be caused by
the illumination of the jet by UV photons from the O star in the system. There may be other X-ray binaries which are associated with EGRET sources. It is already known that Cen X-3 is an EGRET source.

The strongly variable nature of microquasars could be a problem for gamma-ray detectors, but with GLAST and especially the new generation of ground-based detectors, the sensitivity is sufficiently high to make observations of rapid flares feasible. In the case of the HESS and VERITAS VHE gamma-ray telescope arrays currently under construction, their sensitivity is such that a flux as low as $3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ will be detectable in just one hour’s observation. This sensitivity is difficult to attain with a space-based instrument.

To get very fast instruments capable of detecting photons with energies of a few GeV, we must probably also think of ground-based instruments. Dr. Aharonian described a project to build five 20-m diameter telescopes at an altitude of 5 km (5@5). This would give good sensitivity at a few GeV, with an effective area five times higher than GLAST. For example, the Vela SNR would be detected in just one second.

In summary, it is clear that there is still a great deal left to be learnt about microquasars, and that studies of these objects and their larger cousins, the AGNs, are linked. Jets may even be a common phenomenon in binary systems. An important key to improving our understanding is multi-wavelength observations, which allow us to ‘track’ emission from jet to accretion disc to dust clouds. — Paula Chadwick & Andy Norton.

SINGLE-OBJECT SPECTROSCOPY WITH INTEGRAL-FIELD UNITS OR SLITS: WHICH LOSES MORE SIGNAL?

By J. G. Robertson

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An integral-field unit (IFU) at the input of a spectrograph allows it to produce an array of separate spectra, one for each spatial sub-area of the target object. The advantages of such spatially-resolved spectra in revealing kinematic structure are well known. Another advantage often claimed for an IFU input is that it avoids the losses of light on the jaws of a slit spectrograph, when observing a (seeing-broadened) single object. While this is true, it is not light loss per se that is the important criterion, but rather the signal/noise loss. When the brightness of the night sky is comparable to or greater than that of the object being observed (a common situation) then the effects of slit losses are relatively diminished. Moreover, the additional losses in practical IFUs are substantial, and affect the core of the seeing disc as well as the wings. The result is that a slit spectrograph will in many cases produce a higher signal/noise in the output data than an instrument using an IFU input.