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Jets in Astrophysics: a Review

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Abstract We discuss observations used to infer the presence of accretion disks in astrophysical sources and the disks' association with evidence for astrophysical jets. We highlight some important results from past and current literature that show parallels between the temporal behavior of an active galaxy (NGC 5128) and a galactic microquasar (GRS 1915+105). In addition, we note the remarkable observations of the time history of SCO X-1 from VLBI data at radio frequencies.

Key words: accretion; accretion disks; stars:outflows acceleration of particles; black hole physics; radiation mechanisms

1 INTRODUCTION

Most astrophysical jets are thought to be powered by accretion processes. Interestingly, the recent data from Chandra and Hubble on the Crab pulsar (Hester et al. 2002) show that a significantly collimated jet can also be produced by a rotating neutron star.

The energy released by accretion onto a compact object can be a significant fraction of the rest mass of the accretion matter. In general, the kinetic luminosity released by accretion is:

$$\mathrm{d}E/\mathrm{d}t \sim (GM(\mathrm{d}m/\mathrm{d}t))/r \ . \tag{1}$$

The escape velocity out of a gravitational potential is,

$$(1/2)mv^2 \sim GMm/r \ . \tag{2}$$

Of course, material falling into an a gravitating object also reaches equivalent velocities. For accretion objects such as a neutron star or the region near a black hole's event horizon, the accretion velocity is very near the speed of light. Therefore, the power that can be generated by such infall is

$$\mathrm{d}E/\mathrm{d}t \sim \eta(1/2)(m/\mathrm{d}t)c^2 \ , \tag{3}$$

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where η is an efficiency factor usually taken to be $\sim 10\%$, and the efficiency for nuclear reactions is $\sim 1\%$. Accretion is therefore a very efficient mechanism from producing very high energy release per unit mass. This is of course the principal reason for the original hypothesis that AGN could be powered by accretion onto compact objects, and it has led us to the familiar sequence of deductions that began to associate astrophysical jets and accretion black holes.

2 JETS IN ASTROPHYSICS

We have gradually become aware that jets are ubiquitous phenomena in astrophysics. It is in fact tempting to connect a broad range of phenomena that manifest extended linear structures with jets produced by processes in accretion disks.

The bi-polar flows in star-forming regions appear to represent one low-energy extreme. The precessing jet in SS433 (see, e.g., Brinkmann & Siebert, 1999) and the galactic microquasars (see, e.g., Mirabel et al. 1992 for a discussion of 1E1740.7−2942; and Cui 1999, and these proceedings for a discussion of GRS 1915+105) seem to occupy the other limit for galactic sources. Of course, active galaxies and quasars, in this view, can be considered the high-energy extreme of their galactic "cousins."

Apparently, the galactic center also has some evidence for jet-like structures in the infrared. This bears out some aspects of the early work by Beall (1979) and Dennis et al. (1982), which showed that the galactic center had hard X-ray emission of a nature kindred to that of AGN.

While we do not generally focus on this when we talk about jets in active galaxies, Seyfert galaxies have linear radio structures which, while extended to 10's and 100's of parsecs, remain confined to their cores. On the other hand, it is well known that elliptical can have jets extending up to 10's and 100's of kiloparsecs. The "standard" model of AGN supposes that all active galaxies are driven by accretion disks of material spiraling onto black holes.

BL Lacs sources are thought to be different only in regard to their orientation with respect to the observer.

Even things as remarkable as γ-ray bursts have not been spared the application of a jet model. For example, Woosley, Zhang, and Heger (2002) suggest that a jet generated during collapse of massive star interacts with the overburden of material in the envelope to produce the intense γ-ray flare seen in γ-ray bursts. In this case, the energetics would be less problematic (provided that the GRBs are at cosmological distances) since any emission observed would be beamed toward the observer.

3 THE FAMILY TREE OF ASTROPHYSICAL JETS

The association of accretion disks and jet production is probably fundamental, the notable exception being the conical jets emitted from rapidly rotating neutron stars. The disks provide both a mechanism to generate the jets and the mass and angular momentum necessary to keep the jet stable. In fact, the example of giant radio galaxies argues that even the jets that appear to be precessing do so in a consistent fashion over time scales on the order of the life time of the jets (i.e., 10^5 years).

Figure 1 shows a possible "family tree" of jet sources. Variants of this figure have been presented in the past (see, e.g., Brinkmann & Siebert 1999; and Beall 1999) with regard to AGN, and a number of authors have constructed similar tables. However, Fig. 1 includes microquasars; bipolar outflows in the star forming regions of giant molecular clouds; and other jet-like structures. This is done to remark on the association posited above. The fundamental physical principals implicit in the figure are the ubiquity of angular momentum, the enormous mass of compact astrophysical objects, and their energetic and inertial properties.

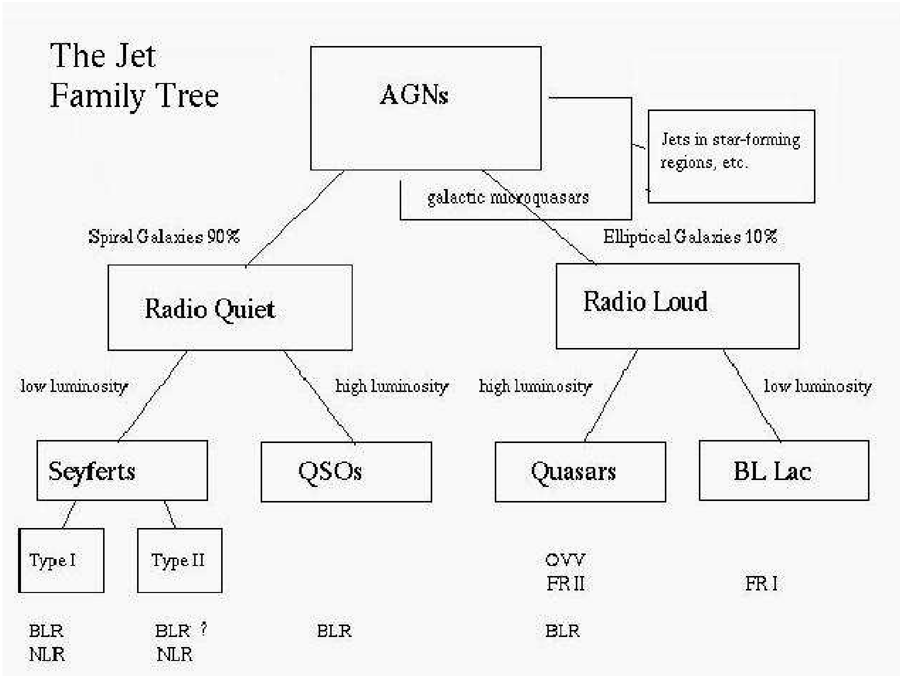

Fig. 1 The family tree of astrophysical jets.

4 EVIDENCE FOR ACCRETION DISKS IN MOLECULAR CLOUDS: THE CASE OF ρ-OPHIUCHUS

Less theatrical but equally important is the consistency of some data from giant molecular clouds and the calculated spectra of a Shakura-Sunyaev accretion disk (Beall 1987). The calculated spectrum in Fig. 2 (Beall 1987) can be shown to be consistent with observations of numerous sources in the ρ Ophiuchus cloud (Lada & Wilking 1984).

The ρ Ophiuchus cloud is particularly interesting because of the presence of bipolar outflows that seem to be associated with sources showing evidence of accretion disks. The bipolar flows are strikingly in evidence in images from the Hubble Space Telescope (HST) (Panagia 2003), and have been shown to have rather high velocities by Tachibara (1998) among others.

5 THE DISK-JET CONNECTION

The disk-jet connection in molecular clouds has been posited by Wilking (1989), among others. Rather detailed scenarios have been developed which show the different classes of sources, depending on the epoch of the evolution of the protostellar system. Figure 4 (from a slide by Elise Furman (Astronomy/Cornell and based on Wilking, 1989) shows the spectral evolution of the disk and its relation to the evolution of the accreting, protostellar system. While the details of this evolution are perhaps uncertain, the general outline presented here must have some validity. In Wilking's view, the jets are an early feature in the evolution of the protostar.

The evidence of protostellar disk evolution in the ρ Ophiuchus cloud is certainly not unique. Based on observations at 850 microns (Greaves et al. 1998), and simulations (Ozernoy et al.

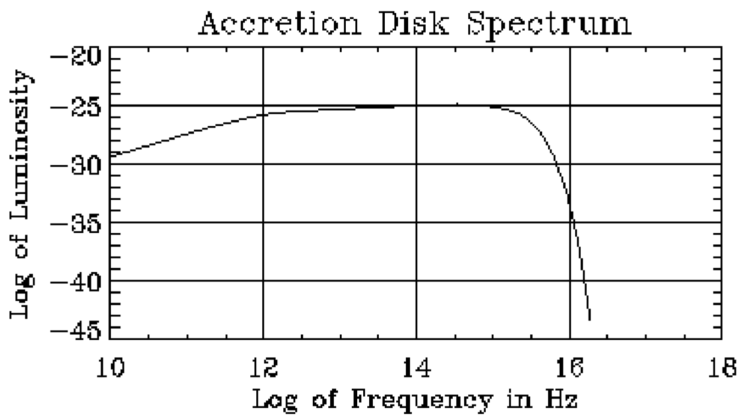

Fig. 2 Spectrum of an accretion disk around a compact object.

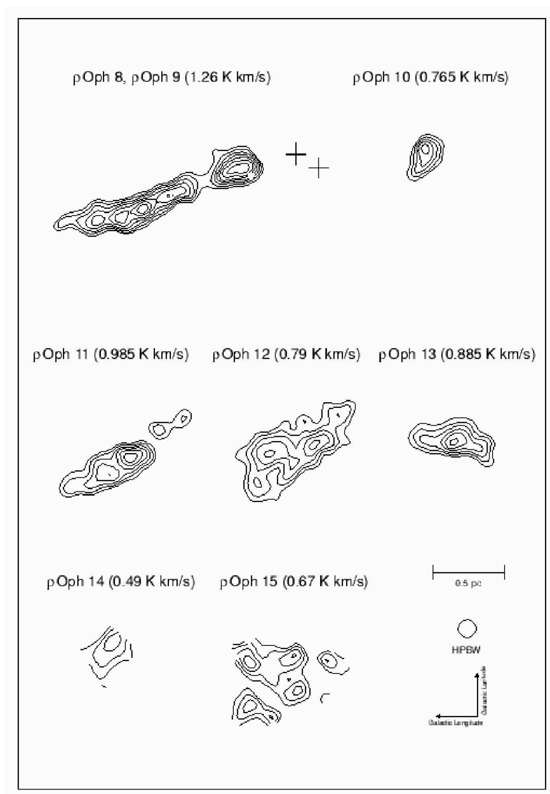

Fig. 3 Bi-polar flows in the ρ Ophiuchus cloud (taken from K. Tachihara's Ph.D. dissertation at Nagoya University, November 1998.

2000), those authors concluded that the debris disks around ϵ Eri ($\sim$ 1 Gyr old) was consistent with a model that includes resonant structures caused by a planet.

6 MICROQUASARS

A great deal of recent work has focused on the so-called galactic microquasars. These efforts can be traced directly to the discovery of the evolving and expanding structure in a galactic source (1E1740.7−2942) at radio frequencies (Mirabel et al. 1992) using the VLA. It thus became apparent that even the cores of normal galaxies contain "baby quasars." This is of course a thesis that Geoff Burbidge posed when the study of AGN was in its infancy. A more complete consideration of these objects is given by Cui (1999) and Parades (1999).

Eikenberry (1999) has presented a series of observations of GRS 1915+105 at radio, infrared, and X-ray frequencies. These data represent the first detection of superluminal motion in a galactic jet. Shown in Fig. 5 are the data in radio, infrared, and X-ray for an interval of roughly one hour during a flare of the source. The hardness ratio in X-rays is also plotted.

If one disregards momentarily the sketch at the top of Fig. 5, and peruses the actual data, it is clear that a number of short X-ray bursts occur at around 08.0 UT and that during these, the radio and infrared luminosities are declining. Thereafter, at around 08.2 UT, the infrared shows a flare beginning at 08.2 UT, peaking at 08.4 UT, and declining to the prior levels at around 08.6 UT. The radio flare is delayed from this, continuing to decline to around 08.3 UT, and then beginning a long rise as the second X-ray flaring episode begins at around 08.3 UT. Eikenberry (1999) interprets these data as being associated with specific episodes of flaring from the disk and the ejection of blobs along the jet axis. The blobs then expand and become optically thin to lower frequencies at later times.

The similarity between this interpretation and the paper on Cen A by Beall et al. (1987) and Beall and Rose (1980) is noteworthy.

7 THE CEN A CONNECTION

The radio, infrared, and X-ray data from GRS 1915+105 are perhaps all the more remarkable when compared with radio and X-ray observations of Cen A (Beall et al. 1978).

The data for the radio and X-ray variability of Cen A presented by Beall et al. (1987) are shown in the upper panel in Fig. 6. The data show the radio flux at three frequency bands (roughly 10.7, 30.0, and 90.0 GHz) during the period from 1969 through 1976. In addition, the lower panel of Fig. 6 shows the low-energy X-ray data from 2−6 keV over the same interval. The infrared data for the core of Cen A are not available because of the enormous amount of obscuration from the dust ring in the source.

The data at radio frequencies show approximately steady-state behavior from 1969 through 1972. In 1973, an X-ray flare increased the source luminosity by a factor of 2. The X-ray flux then appeared to go through a long flare, peaking somewhere around 1974–1975, and then declining to roughly the previous level by late 1976. During the time from 1973 through 1975, the radio data in all three observed bands show a flare which roughly tracks the soft X-ray flare. The picture at 10.7 GHz is rather complicated, because the source is self-absorbed at that frequency, but a general trend that follows the higher frequency variability is evident. This report is the first observation of concurrent radio and X-ray variability of an active galaxy (Beall et al. 1978). Remarkably, the radio data in all three frequencies goes through a second flare from 1976 through mid-1977, even though the X-ray flux seems to continue to decline.

Thus, both the GRS 1915 data and Cen A show complex behavior, with apparent concurrent flaring in some intervals. Furthermore, the data show delays between the short time scale X-ray flaring and the evolving radio (and in the case of GRS 1915, the infrared) data.

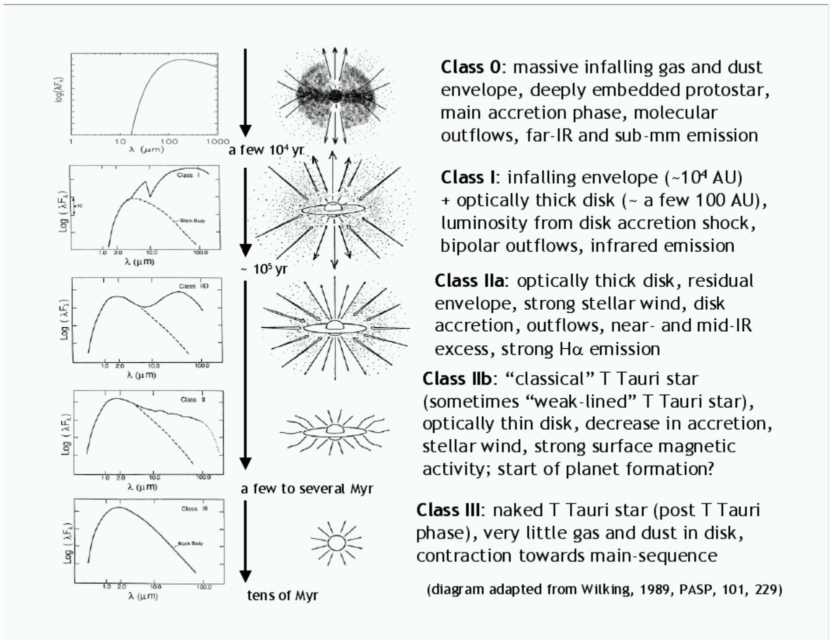

Fig. 4 Disk spectrum and jet production: Elise Furman's adaptation of a figure from Wilking (1989).

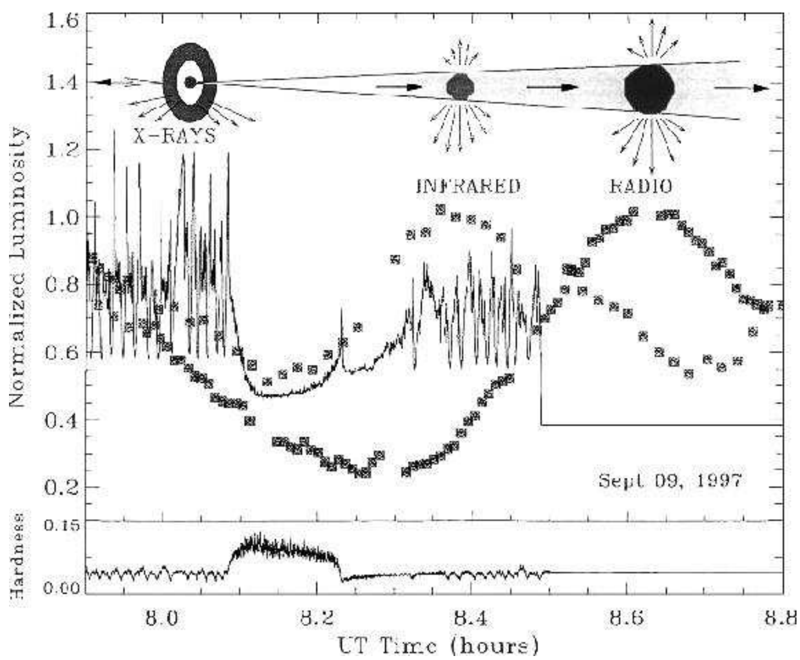

Fig. 5 Temporal and spectral variability of GRS 1915+105, adapted from Eikenberry (1999).

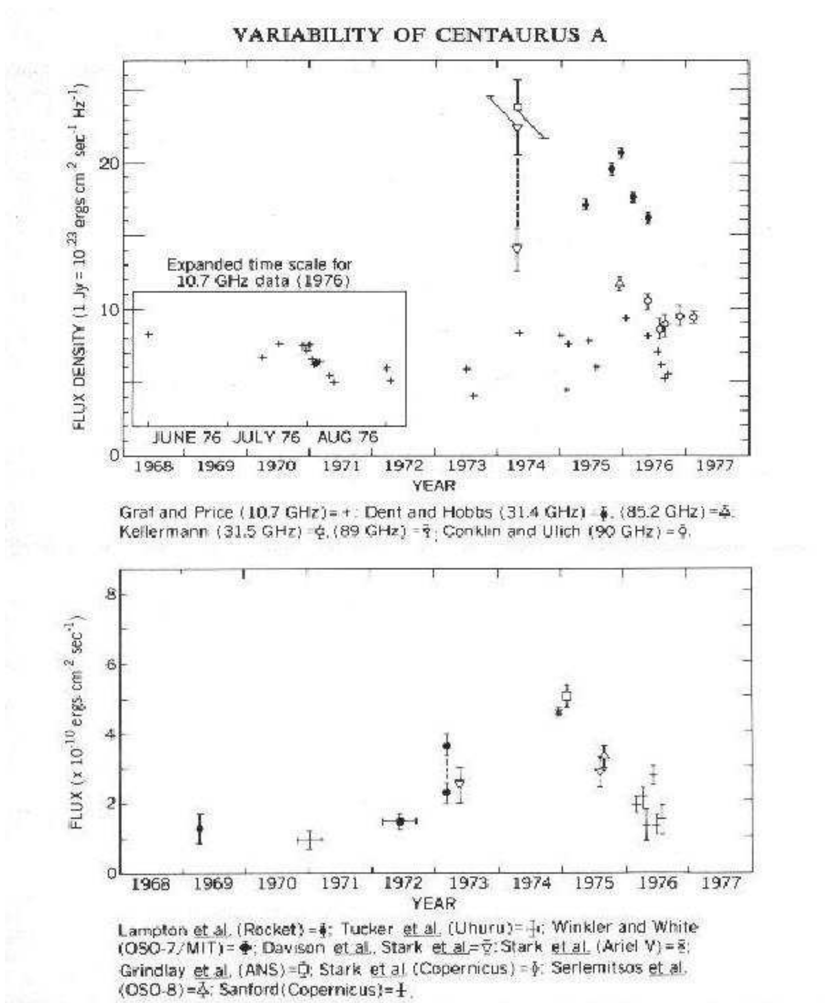

Fig. 6 Radio and X-ray variability of Centaurus A (NGC 5128), Beall et al. 1978.

Beall et al. (1978) also show that the hard X-ray data for Cen A follow the same flaring pattern as that of the soft X-ray. In addition, they establish a hardness ratio that shows that the spectrum of the radiating particles changes, suggesting ongoing particle acceleration during the flaring process.

The mechanisms for the radio and X-ray production are posited to be some combination of synchrotron and inverse Compton radiation (Beall & Rose 1980). The source photons for the inverse Compton scattering is believed to be either radio photons from the compact synchrotron source, or blackbody photons from a thermal source, a model they termed the blackbody-Compton mechanism. Beall et al. (1978) and Beall and Rose (1980) favored the blackbody-Compton model because of the complexity of the temporal behavior of NGC 5128, and their model bears many similarities to the models currently posited for "Blue" blazars.

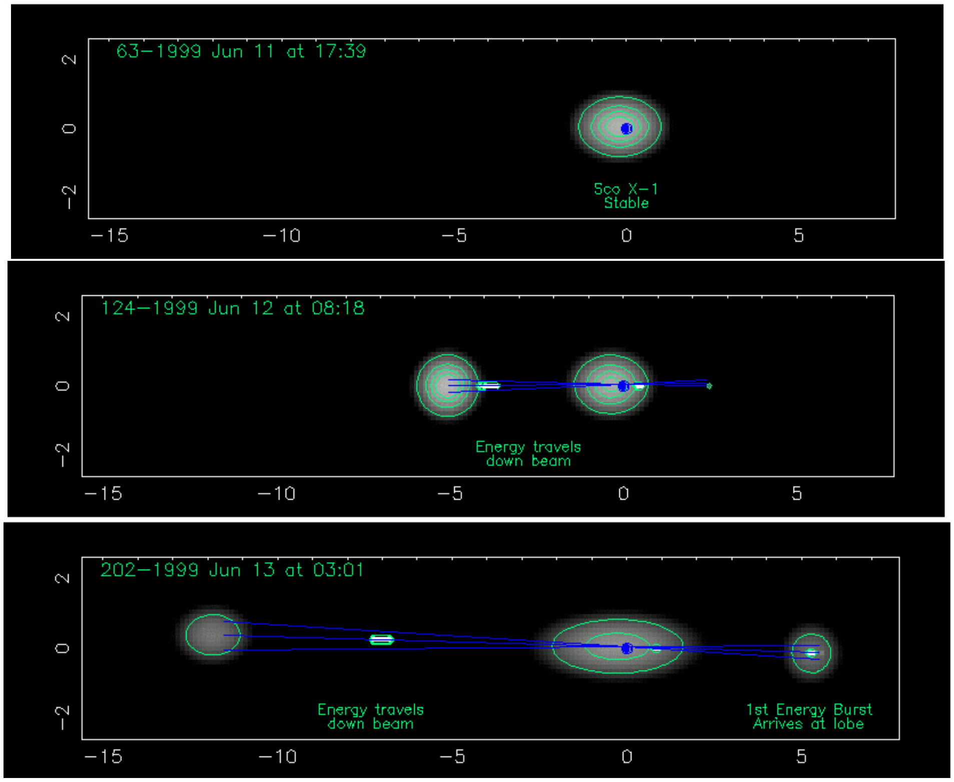

Fig. 7 Snapshots taken from the "movie" of the flaring, jet production, and jet evolution the galactic X-ray binary, Sco X-1 (Fomalont et al. 2001).

We have thus outlined a comparison of the data on the temporal and spectral evolution of the radio to X-ray variability; on the one hand, of an active galaxy, and on the other, of a galactic microquasar. In doing so, we can establish an outline of source evolution that shows remarkable similarities between these two different sources over widely varying time scales (i.e. hours in the microquasar and years for Cen A). Of course, it has been noted that it is much more likely to see the evolution of microquasars, but this has only recently become true because of the availability of the remarkable instruments of the present epoch.

8 THE SAGA OF SCO X-1

Perhaps the most remarkable saga regarding the discovery of quasar-like activity in galactic sources comes from the decades long investigation of Sco X-1 by Ed Fomalont, Barry Geldzahler, and Charlie Bradshaw (Fomalant et al. 2001).

These data form a time-lapsed "movie" over the period of 0400 UT, 11 June 1999 through 0900 UT, 13 June 1999, that is, roughly two days. Some snapshots of the movie are shown in Fig. 7. While the snapshots do not do justice to the actual "movie," a number of observations of these episodes are in order. A detailed discussion of these remarkable data can be found in Fomalont, Geldzahler, and Bradshaw (2001). My own brief commentary follows.

First, the movie begins after an initial flare of the central binary system has already occurred, an event most likely seated in the accretion disk around the compact object. Material has apparently been ejected along an axis inclined from the plane of the sky so that material is flowing at some angle both toward and away from the observer (i.e., like a classic radio jet from an AGN). The relativistic beaming effects are manifest in the intensity ratios of the two lobes, which have apparently been ejected earlier from the source. The first panel shown in Fig. 7 is at the time when these first two lobes have faded from sight at frame 63 on 11 June 1999 at 17:39 UT.

The second panel in Fig. 7 (frame 124 taken on 12 June 1999 at 08:18 UT) shows the system after the ejection of an "overburden" of material from the disk (in both directions). These also show relativistic beaming effects. The small blobs intermediate between the central source are moving with an apparent velocity at or slightly above the speed of light. These small blobs appear asymmetric with respect to the central source because of relativistic effects. When the blobs strike the larger, leading lobes, these lobes flare, indicating that a significant amount of energy has been deposited into the beam "head."

The third panel in Fig. 7 shows a later time (frame 202 taken on 13 June 1999 at 03:01 UT) when the furthermost lobe is again a target for another fast-moving blob of material. At this moment, the pair of relativistic blobs moving along the jet axis toward the lobes shows the time delays. The blob moving toward the observer appears to be halfway to the lobe, while its counterpart is shown dimmer and to the immediate right of the central source. The blob which is striking the right lobe is the receding component of an earlier ejected pair.

These remarkable pictures of Sco X-1 at radio frequencies, together with the movie of the jet in the Crab Nebula taken by the Hubble telescope at optical and the Chandra telescope X-ray wavelengths (Hester et al. 2002) and in these proceedings, show the importance of detailed studies of the temporal evolution of these sources.

9 CONCLUDING REMARKS

The association of accretion disks and astrophysical jets is manifest in sources ranging in energetics from star-forming regions, through microquasars, to active galactic nuclei and quasars.

The historical record for the radio and X-ray variability of Centaurus A (NGC 5128) can be of interest when compared to the time evolution of the galactic microquasar, GRS 1915+105, when the different time scales of the sources are taken into account.

Additional comparisons of the historical evolution of other extragalactic jets and microquasars may shed light on the processes in both.

Furthermore, it seems clear in light of the the Sco X-1 video, that the detailed evolution of a source can be much more complicated than even a series of sequential still images can reveal. This argues for more time-sequenced observations of galactic microquasars in multiple wavelength bands. *The emphasis on multiple-wavelength, concurrent observations of astrophysical sources has been a principal emphasis of the Vulcano Workshops since they began. In fact, this workshop was the first to emphasize such an approach.*

Finally, given the remarkable behavior of the radio jets in Sco X-1, it is possible that the definition of microquasars might need to be expanded to include neutron star accretion systems for galactic sources. This in turn suggests that accretion disk physics close to a compact object may be the original cause of all astrophysical jets.

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