VERY HIGH ENERGY EMISSION IN ACCRETION ONTO COMPACT OBJECTS

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Summary

The production of cosmic ray particles at very high energies (>1 TeV) is required by the recent detections of very high energy (VHE) gamma ray emission from a variety of compact objects. Non thermal radio emission in compact x-ray sources, which are powered by accretion and otherwise display thermal emission processes, points to significant production of high energy particles. In several of these systems, it appears that the production of high energy particles is in fact the dominant source of energy loss and that this occurs with remarkably high efficiency. Constraints on source models and evolution are briefly discussed.

Introduction

The physics of high energy particle production and interactions in astrophysics is becoming increasingly intertwined with the physics of compact objects. Although it has long been suspected that somehow the highest energy particles observed in nature, the cosmic rays extending in energy to values greatly exceeding those available in the largest accelerators, may be produced by tapping a small fraction of the relatively large energy released in violent phenomena such as supernova or stellar flares, it now appears that cosmic rays may be the major end products of processes occurring in and around certain classes of compact objects. By compact objects, we mean collapsed objects such as neutron stars and black holes, or the endpoints of stellar evolution.

We shall review evidence that compact objects undergoing accretion flows (usually from binary companions, but also as isolated objects) may liberate a large fraction of their energy in the form of VHE (and higher energy) particles and photons. Our discussion will center on the compact x-ray binaries: neutron stars (or black holes) undergoing accretion from a "normal" star binary companion. The arguments for cosmic ray production are based on recent gamma ray (at VHE energies and above), x-ray and radio observations of objects such as Cyg X-3. Although the Cyg X-3 results, and claims, are becoming relatively well known, we shall also mention other results (e.g. radio) on Cyg X-3 and other compact x-ray binaries, as well as some related theoretical studies, which may further elucidate the nature of these puzzling objects and the particle accelerators they must contain.

Observational Studies

Observations at a variety of wavelengths support the view that particle acceleration and non-thermal processes play important roles in the physics of compact objects. The most direct evidence comes from observations of VHE gamma ray emission from x-ray binaries, but x-ray and radio observations are also important and can provide more detailed information.

VHE Gamma Ray Results

At energies above about 0.1 TeV, the ground-based atmospheric Cerenkov technique can be used to detect cosmic gamma rays as anisotropies in either the spatial or temporal distribution of extensive air showers recorded from the direction of a suspected gamma ray source. Whereas the first decade of searches for sources yielded evidence[1] for four detections (the Crab pulsar, Cyg X-3, Cen A and the Vela pulsar), the greatly increased activity of the past five years has produced evidence for several more. The most promising of these are the x-ray binaries Her X-1 and 4U0115+63, as recently discussed by Lamb[2]. The Her X-1 detections appear to be at a range of phases of both the 1.7 day binary period and the 35 day precession period of the system indicating that the emission region is not closely tied to the x-ray emission region[3]. In addition, the emission is highly sporadic, being detected only ~8% of the time.

When detected, the VHE gamma ray emission from compact x-ray binaries has apparent luminosity comparable to that detected in x-rays (1-10 keV). Since the emission is typically detected only perhaps 10% of the time, which may be due to variable beaming geometries in the source[2], and the total radiative efficiency of most gamma ray production processes is (considerably) less than 10%, it appears that most of the luminosity of at least some of these objects may be in the form of high energy cosmic rays as is discussed further below.

X-ray Observations of Note

The x-ray spectra of compact x-ray binaries are predominantly thermal in character, with most of the luminosity radiated from blackbody emission from the neutron star surface and from the (inner) accretion disk[4]. In addition these components may be Comptonized by a hot corona surrounding the accretion disk, as suggested[5,6] (by eclipse and light curve data) for a number of sources including Cyg X-3. Only in a few cases is there evidence for a hard x-ray spectral component extending up into the soft gamma ray range (i.e. in excess of 100 keV) which may have a non-thermal origin. Sources with such components in their spectra include Cyg X-3 and the black hole candidates such as Cyg X-1 and GX339-4. The remarkable x-ray binary SS433 with (precessing ?) x-ray (as well as radio and optical) jets also shows an apparently non-thermal power law spectrum at least during certain epochs.

Whereas the simultaneous radio and x-ray flares in SS433 strongly suggest this component of the x-ray emission is non-thermal and closely connected with high energy particle production in the source[7,8], this is not necessarily the case for the other sources with hard x-ray components.

Most notably, Cyg X-3 does not show a detailed correlation between its lower energy x-ray emission and its low-level radio flares[9] as seen in SS433; it remains to be seen whether higher energy x-rays from Cyg X-3 are possibly correlated.

However, it is possible that the lower energy x-rays (2-10 keV) in compact x-ray binaries, which are a direct measure of the accretion energy and mass transfer rate, are indirectly related to the production of high energy particles. In Sco X-1, it has been suggested that the source produces its most numerous radio flares when it is in a relatively low intensity x-ray state and that in this state the x-ray and optical emission is anti-correlated. This could be due to the enhanced effect on the disk of the spinning and magnetized neutron star in this system[10]. When the mass transfer and accretion is reduced, the magnetospheric radius of the neutron star will extend further out into the accretion disk beyond the co-rotation radius (i.e. where the local Keplerian velocity of material orbiting in the disk is lower than the rotation velocity of the magnetic field anchored to the neutron star). In this case, neutron star spin energy can be released into the disk due to the drag of the disk on the star, and this energy may be lost into magnetic reconnection.

Radio Observations of Compact Binaries

Perhaps the most direct evidence that high energy particle production is occurring in compact x-ray binaries is the variable radio emission which they typically produce[11]. This emission is undoubtedly due to synchrotron radiation from particles in source regions which are typically $\sim 10^{12}$ cm (for the low mass x-ray binaries such as Sco X-1) to $\sim 10^{14}$ cm (for the high mass systems such as SS433) and are thus significantly larger than the characteristic dimensions of the binary systems. These source sizes are inferred from the models discussed in the next section below.

In at least three compact x-ray binary sources (Sco X-1, Cyg X-3 and SS433), the radio emission is produced in expanding jets. The double radio lobes of Sco X-1 are indicative of the ejection and expansion of relativistic plasma, and indeed the proper motion of the lobes has now finally been measured[12]. Similarly, recent VLBI studies[9,13] have directly measured the expansion of the Cyg X-3 jets to be approximately 0.3c (for assumed values for the source distance and inclination), or comparable with that directly observed (in the optical) for the jets in SS433. In all of these cases, however, there is no evidence that the non- thermal emission is itself beamed. Rather, the radio through x-ray (in the case of SS433) appears to be isotropic within the jets so that the particle production is itself isotropic in these accretion-fed sources.

The radio emission, and thus the production of high energy particles, appears to be highly variable in compact x-ray binaries. In the most spectacular case, the radio emission from Cyg X-3 undergoes giant radio outbursts approximately once per year (and possibly periodic) as well as much smaller flares in its quiescent emission with a period of 4.95 hours[9]. This period is of course different from the well known 4.79 hour binary period of the system and, if confirmed, suggests fascinating possibilities (see discussion below) for the nature of the Cyg X-3 system. The radio flares of SS433 may also recur with a period related to (but not identical with) its 13 day binary period[8]. Again, the interpretation of this constrains the nature of the binary system. In both cases the possible offset of the radio periods from the binary periods suggests that the searches for VHE gamma rays (or higher energy emission) at the exact binary period may be too simplistic. If the particle production resulting in the radio flares is related to the particle production and interactions resulting in VHE or UHE gamma ray emission, then these offset periods must be searched in the data sets.

In the case of the luminous compact x-ray binaries like Sco X-1 (the so- called galactic bulge sources and those sources in globular clusters), the radio emission is highly sporadic on timescales of hours to days[11] but has not yet been found to be periodic. The fact that the emission is much weaker in these sources than in Cyg X-3 or SS433, however, obviously makes searches for periodicities much more difficult. The generally southern declinations of these galactic bulge sources also makes the long coverages desired for periodicity searches generally impossible from the prime radio telescope, the VLA, in the northern hemisphere. Long-term radio studies of the prime candidates for VHE gamma ray emission, Her X-1 and 4U0115+63 (in addition to Cyg X-3), could be carried out with the VLA and should be. This might establish whether the production of high energy particles, which must be near the neutron star in these systems since pulsed TeV gamma rays are seen, is modulated by external factors in the binarysystem.

Theoretical Studies

The theoretical work on high energy particle emission processes in x-ray binaries has developed along two distinct lines: that the fundamental mechanisms are pulsar-like, where particle acceleration occurs due to the strong electric fields set up by the rotating magnetized neutron star[14], or that the particle acceleration occurs as a consequence of the magnetic fields entrained in the accretion disk and the orbital motion of ionized plasma in the disk[15]. There are at least two obvious reasons for preferring the second (e.g. accretion) mechanism: TeV emission is detected from accretion sources in which the vacuum pulsar mechanism is difficult to imagine not being "shorted out", and the sources such as Her X-1 and 4U0115+63 are relatively slow rotators for which the induced electric fields would be expected to be much less than in a fast pulsar like the Crab. Thus we agree that particle acceleration in or near the accretion disk is the more likely mechanism.

A Triple Star Model for Cyg X-3

Since both the radio and gamma ray emission in x-ray binaries appears to be sporadic, it is interesting to ask what the

total energetics are. In Cyg X-3, the low level radio flares display a frequency vs. time behavior characteristic of an expanding synchrotron source[9]. Thus the approximate location and total energy of the initial particle distribution which must be created at the onset of the flare can be estimated. As mentioned above, the source size is then derived to be approximately 10^{12}cm, and its total energy some 10^{41} ergs. Since the time between successive flares is approximately 4.9 hours, the time averaged luminosity in relativistic particles in Cyg X-3 must be at least 10^{37} ergs/sec, or comparable to the total x-ray luminosity. This may be only a lower limit since the energies of the radio-emitting synchrotron electrons are low (with Lorentz factors $\gamma \sim 10^3$), and the spectrum undoubtedly extends to much higher energies to explain the gamma ray results.

The flare trigger in Cyg X-3 may be a third star orbiting the x-ray binary, since such a hierarchical triple system could not only explain the offset period (as a beat between the binary and tertiary periods) but could also explain the possible phase jumps seen in the times of the radio flares[16]. A triple companion star in the Cyg X-3 system with the correct period(~ 4 days) would in fact orbit at about $\sim 10^{12}$ cm from the binary and would induce periodic changes in the separation of the inner binary components (the neutron star and its companion in the 4.8 hour orbit) which recur every 4.95 hours.

This induced change in binary separation would cause a change in the local mass transfer rate and a corresponding change in the magnetospheric radius of the neutron star. If the neutron star is assumed to have spun up to its equilibrium period (when neither spin-up or -down torques are applied on average since the magnetospheric, or inner disk, radius is at the co- rotation radius for matter in the disk), then sudden increases in magnetospheric radius can dump energy into the disk (every 4.95 hours). As mentioned above, this would possibly take the form of magnetic field reconnection as the neutron star magnetic field is "pulled back" and annihilated by a possible poloidal magnetic field in the disk. The liberated energy might be expected to drive material off the disk along open field lines, assumed axial (for the assumed poloidal disk field), to form the jets with velocity ~0.3c by the same line locking mechanism[17] as in SS433. Particle acceleration to relativistic energies could then occur in shocks at the radius of the tertiary companion where the jet crosses the shell of mass lost from the tertiary due to x-ray heating. For the shell to subtend the jets, the tertiary must be in a highly inclined orbit to the plane of the binary; such orbits are stable up to inclinations of at least[18] 60°.

In this model, if the VHE gamma rays are produced at the acceleration site, time variations in the gamma rays are not expected on time scales below ~100 sec. This would be so if the gamma rays are produced in electromagnetic interactions (e.g. synchrotron self-Compton models) in the radio source volume. However, if the gamma rays are produced instead by hadronic interactions of relativistic protons accelerated in the shocks which then travel back down along the jets to strike the thick target of the accretion disk, then shorter timescale fluctuations are allowed. In this case, also, the primary modulation of the VHE gamma rays can be at the 4.8 hour binary orbit, as apparently observed, rather than the 4.95 hour radio (i.e. flare injection) period, since the gamma ray production in the disk would still be eclipsed by the secondary star in the binary system.

Conclusions

We have reviewed various arguments for the general importance of non- thermal particle emission processes in compact x-ray binaries. These sources, which are usually viewed as being primarily thermal objects, can liberate a large fraction (perhaps most) of their ultimate gravitational energy store in non-thermal particles. The details of both the observational and theoretical picture are hazy at best. On the observational side, long duration radio observations are needed of a number of these systems to establish the systematics of the ubiquitous flaring behaviour. In Cyg X-3 more detailed and long duration radio observations are needed to confirm the apparent 4.95 hour period and the inferred triple nature of the system. Since triple systems are implicated[19] for a number of galactic bulge x-ray sources, including the bright source (and variable radio source) GX17+2 whose possible binary (1.4 hours) and tertiary periods (6.5 days) may not be very different from Cyg X-3, the triple nature of Cyg X-3 might not be too surprising.

Much more convincing, and confirming, observations at VHE (and UHE) energies are also needed. At the moment, with the wide variety of effects claimed for a wide range of times and phases in a number of x-ray binaries, it is difficult to describe the phenomena accurately enough to construct convincing models. General scenarios can be created, such as that drawn here for Cyg X-3, but more detailed theoretical treatment remains for the future. The prospects for progress, both observational and theoretical, are tantalizing and the next steps should be taken.

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