ULTRA HIGH ENERGY GAMMA RAYS, COSMIC RAYS AND NEUTRINOS FROM ACCRETING DEGENERATE STARS

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ABSTRACT

We here consider implications of having super-Eddington accretion for our recently proposed unipolar induction model of cosmic ray acceleration in accreting binary star systems containing magnetic white dwarfs or neutron stars. For sufficiently high accretion rates and low magnetic fields, the model can account for: (1) acceleration of cosmic ray nuclei up to energies of 10^{19} eV; (2) production of more or less "normal" solar cosmic ray composition; (3) the bulk of cosmic rays observed with energies above 1 TeV, and probably even down to somewhat lower energies as well; and (4) possibly the observed anti-proton cosmic ray flux. It can also account for the high UHE gamma-ray flux observed from several accreting binary systems (including Cygnus X-3), while allowing the possibility of an even higher neutrino flux from these sources, with $L_\nu/L_\gamma \sim 10^2$.

1. Introduction. VHE($>10^{12}$ eV) and UHE($>10^{15}$ eV) gamma-ray emission has been reported from the x-ray source Cygnus X-3. Four binary x-ray sources (LMC X-4, Vela X-1, Her X-1 and 4U 0115 +63) have also been reported as VHE or UHE gamma-ray sources (cf. ref. (1) for a summary of results up until February, 1985). The nature of Cygnus X-3 is unclear, but owing to its many similarities with other "normal" accreting binary x-ray sources, we assume that it is a mass transfer binary system with a 4.8 hour orbital period, and exhibiting phenomena associated with mass transfer from a more-or-less normal star onto a magnetized neutron star. Though some longer periods have been associated with the source, no short time scale behavior indicating an underlying neutron star rotation period has been reported.

In reference (1), we proposed a model for the acceleration of particles to high energies in accreting binary systems containing magnetic neutron stars or white dwarf companions of a normal star. The physical basis of the present model (originally suggested by Lovelace (2) as a model of particle acceleration by accreting black holes in galactic nuclei or quasars) is the idea that unipolar induction operating in an accretion disc can lead to a large potential drop across the disc. This can then lead to acceleration of particles (protons, electrons or nuclei) to high energies when they traverse the region containing the potential drop. Details of the electrodynamics are, admittedly, obscure. How is the electrical "circuit" closed? Why isn't the induced electric field shorted out? Is the current flow steady or is it variable, with short "lightning"-like discharges? And so on. Nonetheless, the simplicity of the model, combined with the apparent facts to be explained and the lack of any viable alternative model for particle acceleration in these systems has prompted us to examine further aspects of the model, even in the absence of a completely self-consistent picture of the electrodynamics (in much the same spirit as pulsar theorists who, 15 years after the discovery of pulsars, persue the analysis of pulsar phenomena in the absence of a consistent electrodynamic pulsar model.)

2. Unipolar Induction Model. The potential drop produced across the disc is given by

$$V = -\frac{(GM)^{1/2}}{c} B_z(r_1) r_1^{1/2} \ln(r_2/r_1). \quad (1)$$

Here M is the mass of the accreting star, B_z is the z component the disc field (B_r, 0, B_z), and r_1 and r_2 are the inner and outer disc radii. The inner disc radius is taken to be the Alfven radius

$$r_1 = 1.8 \times 10^8 B_{12}^{4/7} R_6^{10/7} (M/M_\odot)^{1/7} L_{38}^{-2/7} \text{ cm}. \quad (2)$$

Here, B, R, and L are the surface magnetic field, radius and total accretion luminosity associated with the neutron star in cgs units as indexed. Not all of this luminosity will appear as accelerated fast particles. It can also be liberated as bulk gas motion (e.g. in a jet perpendicular to the accretion disc, as is observed in both Cygnus X-3 and the peculiar object SS433) and radiation. Clearly the particle luminosity L_{part} must satisfy $L_{part} < (GM/r_1)\dot{M} = LR/r_1$, since particles can only begin to accelerate at the inner edge of the accretion disc. The maximum particle luminosity can be found by assuming the "resistance" of the "circuit" is c^{-1},

$$L_{part,max} = 2cV^2 = \frac{2GM}{c} B_z^2(r_1) r_1 (\ln(r_2/r_1))^2. \quad (3)$$

The above relations can be combined to form a scaling law for the dependence of the potential drop V (or maximum accelerated particle energy W = qV) on the accretion luminosity L (which is proportional to the accretion mass transfer rate $\dot{M}$) and on the (assumed dipolar) neutron star surface magnetic field

$$W_{max} \propto B^{-3/7} L^{5/7}. \quad (4)$$

This result implies that for a given magnetic field strength, provided that $r_1 > R$, the higher the accretion rate, the larger the maximum particle energy which can by attained, and the higher the total particle luminosity. Is there a limit to the energetic output of such systems?

3. Super-Eddington Accretion. In general, accretion flows in binary sytems have been assumed to be Eddington limited. The resulting accretion luminosity L_{Ed} is determined solely by the mass of the accreting object, M, the cross section for absorbing radiation (in the case of photons, simply the Thompson cross-section σ_T) and physical constants: $L_{Ed} \simeq 4\pi cGMm_p/\sigma_T \simeq 1.3 \times 10^{38} (M/M_\odot)$ erg s^{-1}. This result depends on two factors. First, that the accretion is spherically symmetric. Second, that the accretion produced luminosity leaves the source in the form of photons. In the present case, however, with disc accretion and with acceleration of protons, neither of these assumptions holds. A detailed "proton-Eddington" limit depends on unknown geometrical factors, as well as

numerical integration of the (energy dependent) inelastic proton-proton scattering cross section over the (unknown) accelerated proton cosmic-ray spectrum. A crude estimate of these factors can be gotten by taking $\sigma_{pp} \approx 60$ mb, and assuming that the disc occupies no more than a steradian (and/or the accelerated particle beam encounters no more than 1 steradian solid angle of incoming accretion material). Then, taking the neutron star to have $M \approx 1.4\ M_{\odot}$, one finds $L_{Ed,proton} \approx 10^{41}$ erg s^{-1}.

Observationally, how does this fit in with Cygnus X-3? First, it should be noted that the total already observed electromagnetic flux from Cyg X-3 (mostly x-rays and gamma-rays) is comparable to the photon Eddington limit. While this may suggest an Eddington limited accretion flow, it does not allow for any inefficiency in the radiation processes of the system, or the possibility of major mass outflow. Both of these apply, however, in this case. First, the only suggestions to date which can account for the observed UHE gamma-ray flux depends on proton-proton produced pion decay gamma-rays. Such a process (even neglecting subsequent photon absorption) is only about 10% efficient. Second, there does appear to be a radio jet emanating from the system, and some models of this (radio) jet suggest that the energy required for this outflow (as in the similar system SS433) is greater than 10^{39} erg s^{-1}(J. Grindlay, private communication). Third, measurements of the (assumed) orbital period variation over time indicates that $\dot{P} \approx 10^{-9}$. To convert this to a mass transfer rate requires a knowledge of the star masses involved (unknown at present), and whether the system is a wind or accretion driven flow (also not known). Nonetheless, for roughly solar mass stars and assuming that no more than half the mass transfer leaves the system, one has that $dM/dt \approx 10^{-6} - 10^{-5}\ M_{\odot}\cdot yr^{-1}$, implying an accretion luminosity of $10^{40} - 10^{41}$ erg s^{-1}.

One further observation has bearing on the question of the possibility of super-Eddington accretion. Ling et. al. (3) have reported the possible detection of an x-ray cyclotron line from Cygnus X-3, implying a surface magnetic field of order 10^{13} gauss. This result is apparently somewhat uncertain. If correct, however, in the present model it requires that the accretion rate be of order $10^{-6}\ M_{\odot}\ yr^{-1}$, in order for a potential of order 10^{17} volts (required to produced the observed 10^{16} eV gamma-rays by pion decay) to be achieved. With such a strong field, it should be noted that only a few percent of the accretion luminosity can be converted to fast protons (because of the large resulting value of r_1), and that most of the energy must be released in the form of a jet. On the other hand, for a somewhat weaker field (say 10^{10} gauss), with such a high accretion rate, both the maximum potential and total particle luminosity will increase over the values suggested in reference (1).

4. Neutrino Binaries. In the present model, we can also compute the fluxes of photons and neutrinos resulting from cosmic ray proton collisions with ambient gas. Two remarks are in order here. First, the production rate of each depends both on the total column density of gas encountered by the acclerated protons, and on the density of the gas. For too high a gas density, the produced pions can lose energy before they decay, thus reducing the resulting neutrino flux. For a high gas column density (>50 gm/cm^2) the resulting gamma-rays can also be absorbed. Therefore, the production spectrum of both gamma-rays and neutrinos depends critically on

the assumed mass distribution. We have considered interaction with the accretion stream for Cygnus X-3, and find the following: for $\dot{M} \simeq 10^{-5} M_{\odot}$ yr^{-1} and $L \simeq 10^{41}$ erg s^{-1}, the density of the gas in the accretion stream is low ($\rho < 10^{-8}$gm cm^{-3}), while the column density can be as much as $\chi \simeq 100 - 300$ gm/cm^2. Thus, while the pions can decay into photons and neutrinos (and electrons), much of the produced gamma-ray flux can be absorbed by the accreting gas, leading to neutrino to photon ratios as high as $10^2 - 10^3$. However, the total resulting particle (and therefore gamma-ray and neutrino) flux from Cygnus X-3 depends on the magnetic field strength as well. For $B \simeq 10^{13}$ gauss, we find $V_{max} \simeq 3 \times 10^{17}$ volts and $L_{part,max} \simeq 2 \times 10^{39}$erg s^{-1}; while for $B \simeq 5 \times 10^{9}$gauss, we find $V_{max} \simeq 6 \times 10^{18}$volts, and $L_{part,max} \simeq 10^{41}$ erg s^{-1}. A simultaneous measurement of the gamma-ray and neutrino fluxes at comparable (say TeV) energies, therefore, can uniquely determine the magnetic field strength in this model. (Of course neutrino production in the companion stellar atmosphere is also likely and would complicate such a comparison.)

5. Origin of Cosmic Rays. Finally, we note that accreting magnetized binaries offer the possibility of accounting for many of the observed properties of cosmic rays. We list these without detailed comment here. (1) For the parameters listed above for Cygnus X-3, iron nuclei can be accelerated to energies of greater than 10^{19} eV. If the most energetic cosmic rays can be nuclei rather than protons, their energies can easily be accomodated by the model discussed here. (2) The total luminosity in our galaxy for all cosmic rays of energy greater than 10^{12} eV is about 10^{39} erg s^{-1}. Even in the strong field model above, Cygnus X-3 can alone provide all (or a significant fraction) or these particles. If the spectrum extends to even lower energies (due to pp collisions on leaving the source as suggested by Hillas (4)),such sources may account for even more of the cosmic ray flux down to lower energies. (3) The composition which results from such electrostatic acceleration of accreted normal stellar material should (depending on ionization and other details) more closely reflect "normal solar" composition than, for example, shock accelerated cosmic rays from supernovae. (4) The present picture can lead to the production of a substantial secondary anti-proton flux from p-p collisions in the accretion stream. Whether these can the be decelerated to produce the observed anomalously high .1 - 1 GeV antiproton flux remains to be seen.

References

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