Gamma-ray Emission from the Cataclysmic Variables I: The Compton EGRET Survey

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GAMMA-RAY EMISSION FROM CATAclysmic VARIABLES. I. THE *COMPTON* EGRET SURVEY

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ABSTRACT

We report the results of the first γ -ray survey of cataclysmic variables (CVs) using observations obtained with the EGRET instrument on the *Compton Observatory*. We briefly describe the theoretical models that are applicable to γ -ray emission from CVs. These models are particularly relevant to magnetic CVs containing asynchronously rotating white dwarfs. No magnetic CV was detected with an upper limit on the flux at 1 GeV of $\sim 2 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$, which corresponds to an upper limit on the γ -ray luminosity of $\sim 10^{31} \text{ ergs s}^{-1}$, assuming a typical CV distance of 100 pc.

Subject headings: stars: cataclysmic variables; γ -rays: observations

1. INTRODUCTION

X-ray and γ -ray emission from accreting compact objects such as white dwarfs, neutron stars, and black holes, has provided us with valuable probes in understanding accretion processes in such sources. Most of the attention on γ -ray emission from compact objects, has focused on accreting neutron stars and black holes, rather than white dwarfs, due to the deeper gravitational potential wells they possess which yield a greater acceleration of matter to γ -ray energies. It is possible to explain the emission of MeV γ -rays at near-Eddington luminosities from accreting neutron stars and black holes, but difficult to do so with accreting white dwarfs. It has, however, been proposed that non-thermal processes operating around accreting magnetized white dwarfs, can produce γ -ray radiation (Chanmugam & Brecher 1985; Cheng & Ruderman 1991). In this paper, we are specifically interested in γ -radiation from cataclysmic variables (CVs) which are close binaries in which a white dwarf accretes matter from a red dwarf. The expected γ -ray luminosity $L_\gamma \lesssim L$, where $L = GMM\dot{M}/R$ is the total accretion luminosity, M the mass of the white dwarf, R its radius and $\dot{M}$ the accretion rate. One expects L_γ to be below that of accreting neutron stars and black holes, assuming similar accretion rates and efficiency of conversion of gravitational energy into γ -rays. But the typical distance (~ 100 pc) to a CV is 10-100 times closer than that of a neutron star or black hole binary, so that the expected flux would be correspondingly higher, and hence CVs are potential contributors to the integrated γ -ray spectrum of the sky.

Mass transfer in CVs generally occurs via a stream that forms an accretion disk. About 25% of all CVs (Ritter & Kolb 1994) have a magnetic field sufficiently strong to disrupt the accretion disk either partially or completely (Cropper 1990; Chanmugam 1992). These magnetic CVs can be divided into two classes, the synchronous rotators in which the white dwarf rotates essentially synchronously, i.e., the rotation period of the white dwarf

P is within about 2% of the orbital period P_{orb} ; and the asynchronous rotators in which P differs more greatly from P_{orb} . The synchronous rotators are generally known as AM Herculis binaries after their prototype, or 'polars', because of the strong optical polarization they emit. The white dwarf in these binaries have surface magnetic fields $B_s \sim 10 - 70$ MG, and the field strength is sufficiently strong to prevent formation of an accretion disk because the magnetospheric radius $r_m \gtrsim a$, where a is the orbital separation. Magnetic interactions between the white dwarf's dipolar magnetic field and the intrinsic or induced dipolar field of the red dwarf can lead to synchronization of the white dwarf (Wickramasinghe & Wu 1994 and references therein). The asynchronous rotators are called the DQ Her binaries by some authors (e.g., Lamb 1985) while others only call them so if the rotation period of the white dwarf $P \ll 0.1P_{orb}$. Those systems for which very roughly $P \sim 0.1P_{orb}$ are sometimes called intermediate polars (IPs). The value of P ranges from ~ 33 s, for AE Aqr, to ~ 2 hr for TW Pic. The asynchronous rotators emit no polarized optical radiation, in general, and hence presumably have weaker magnetic fields $B_s \ll 10$ MG, than the AM Her binaries. Their magnetic field strength must nevertheless be larger than about 5×10^4 G to channel the accretion flow onto the polar caps of the white dwarf, thereby producing radiation at optical and X-ray wavelengths modulated at the rotation period. Two exceptions are BG CMi from which weak optical/IR polarization has been detected (West, Berriman, & Schmidt 1987) with a magnetic field $B_s \sim 4$ MG (Chanmugam et al. 1990), and RE 0751+14 from which somewhat stronger polarization has been detected with $B_s \sim 8 - 18$ MG (Piirola et al. 1993). It is generally believed that the DQ Her type binaries have accretion disks but it is controversial as to whether an accretion disk does or does not form in all of the IPs (see, for example, Hellier 1992; Norton et al. 1992).

A few detections of γ -ray emission from magnetic CVs have been reported. The DQ Her type binary AE Aqr has been reported to have been detected in the TeV range (Meintjes et al. 1992; Meintjes et al. 1994), with evidence for a quasi-periodic signal at

~ 30 mHz in 10% of the observations. This feature is red-shifted by $\sim 0.7\%$ with respect to the spin frequency; similar small redshifts are observed in the optical (e.g., Patterson 1979). No steady component of TeV γ -rays has been found. Bowden et al. (1992) reported a 6σ detection of a 1 minute burst from AE Aqr; it was shown to be 100% pulsed with a very hard energy spectrum relative to the cosmic ray spectrum. Meintjes et al. (1994) also reported the detection of a few, closely-spaced, 1-minute bursts (peak significance 4.6σ). A summary of the thermal and non-thermal properties of AE Aqr are given by De Jager (1994). Bhat et al. (1991) have reported the detection of TeV gamma rays from AM Her with a luminosity $L_\gamma \sim 10^{32}$ erg s $^{-1}$. These reports together with the theoretical predictions have motivated us to search for γ -ray emission from CVs using the EGRET, COMPTEL, and OSSE instruments on the Compton Observatory.

In Section 2 of this paper, we summarize the models that have been developed to explain, or to predict, γ -ray observations of neutron stars and black holes in close binary systems. Since most of the corresponding papers do not discuss γ -ray emission from CVs in much detail or at all, we do so to test the low-power limit of these models and the predictions of particle acceleration efficiencies. In Section 3 we describe the EGRET data and its analysis, while in Section 4 we discuss the observational results and consider the implications of the non-detections. Future papers will focus on observations with COMPTEL and OSSE.

2. MECHANISMS FOR γ -RAY EMISSION

In this section, we briefly review the proposed mechanisms and apply them to CVs. Four general mechanisms, and variations thereof, have been proposed to create γ -rays: (i) the pulsar mechanism (Goldreich & Julian 1969; Ruderman 1989); (ii) the Fermi mechanism (Eichler & Vestrand 1985; Kazanas & Ellison 1986) or the diffusive shock-acceleration

mechanism; (iii) the unipolar-inductor mechanism (Blandford 1976; Lovelace 1976), and (iv) magnetic reconnection events (e.g., Tavani & Liang 1993). For each of these mechanisms, high-energy charged particles are accelerated and produce γ -rays through collisions with matter, for example in the accretion disk. Accelerated protons can then interact with matter to produce pions; γ -rays arise from the resulting π^0 decay. Accelerated electrons convert a significant amount of energy to γ -rays via inverse Compton scattering provided the photon field is sufficiently intense.

The first mechanism has been applied to rotation-powered pulsars. The magnetic CV systems should also fulfill the conditions of the model, namely, a rotating, magnetized, white dwarf. A potential difference ($>10^{14}$ V) (Cheng, Ho, & Ruderman 1986; Ruderman 1989) is induced along the open field lines. Plasma is pulled from the surface of the star until $\mathbf{E} \cdot \mathbf{B} = 0$ outside the star (the relation is already satisfied within the star). The material outside the star creates a corotating magnetosphere with a charge density (Goldreich & Julian 1969)

$$n \sim |\Omega \cdot \mathbf{B}| / (2\pi e c) = 7 \times 10^3 \mu_{32} r_9^{-3} P^{-1} \text{ cm}^{-3}, \quad (1)$$

with μ_{32} the magnetic moment of the star in units of 10^{32} G cm³ and $r_9 = r/10^9$ cm. Charge separation (the "outer gap") occurs that is dictated by the sign of $\Omega \cdot \mathbf{B}$ in various regions of the magnetosphere. An $e^\pm$ pair, produced in the gap, is separated and accelerated. Multi-GeV γ -rays are generated by curvature radiation. For the Crab pulsar, for example, the pair production is estimated to be $\sim 10^{39} \text{ s}^{-1}$ (Ruderman 1989). The model has been applied to the "slowly-rotating" Geminga (rotation period 0.237s) (Ruderman et al. 1993).

The second mechanism appears most applicable to the AM Her binaries, but one cannot rule out its applicability to the asynchronous rotators. The fundamental process in the diffusive shock mechanism is the acceleration of particles by repetitive scattering

back and forth from scatterers which exist on either side of the shock. The efficiency of the acceleration process is directly related to the number of particles scattered back and forth. Kaul et al. (1993) have developed the model to explain the reported TeV emission from AM Her. In their model, the shock forms at a radial distance $\sim 20 R$, the radius at which the ram pressure of the accretion stream equals the magnetic pressure. The high energy particles produced collide with matter in the accretion column and produce γ -rays.

The column density necessary to produce the γ -rays is obtained by integrating the density along the line-of-sight through the accretion funnel. For some geometries, different column densities for different lines-of-sight produce an orbital modulation of the signal. Schneider (1993) also develops the diffusive particle acceleration model and applies it to turbulent regions. The specific addition to the theory is the development of the effects of an ensemble of shocks. He specifically applies the model to regions in which many shocks exist due to macroscopic turbulence. The diffusive shock model is usually invoked for the AM Her binaries; Schneider's variation implies that it may be applicable to accretion disk systems, i.e., the DQ Her binaries. Spiral shocks have been predicted to occur in accretion disks (e.g., Spruit 1987). Spruit (1988) reported the results of a study of particle acceleration in the shocks of an accretion flow, but the conditions used were applicable to AGN. Based upon numerical studies (e.g., Sawada et al. 1987; Matsuda et al. 1990) in which the CV disks appear to show only a few shocks (similar in appearance to the few-armed spiral galaxies), the diffusive acceleration of particles by shocks may not produce sufficiently energetic particles in CVs. The diffusive mechanism requires particles to traverse either one shock many times or many shocks once. Either situation may not describe CV accretion disks.

The third mechanism was originally applied to accreting supermassive (mass $M \sim 10^8 M_\odot$) black holes where strong magnetic fields were claimed to be produced in the disk by dynamo action. It was then applied, with modifications, to X-ray binaries

containing magnetized neutron stars by Chanmugam & Brecher (1985), who suggested that it was also applicable to the DQ Her binaries such as AE Aqr. If the angular velocity of the disk is Ω_d and the angular velocity of the star is Ω , the charged particles experience a radial electric field given roughly by

$$E_r(r) \sim \frac{1}{c}[u_\phi(r) - \Omega r]B_z(r), \quad (2)$$

where $B_z(r) \sim B_s R^3/r^3$, and $u_\phi(r) = \Omega_d(r)r$ is the azimuthal disk velocity. By tacitly assuming that $\Omega = 0$, integrating the electric field across the disk, and assuming that the outer radius of the disk is much larger than the inner radius r_1 , Chanmugam & Brecher found that the maximum potential drop is

$$V_{max} \approx \frac{2(GM)^{1/2}}{5c} \frac{\mu}{r_m^{5/2}}. \quad (3)$$

Here, $r_1 \sim r_m$ = the magnetospheric radius (Ghosh & Lamb 1991), $\mu = B_s R^3$ is the magnetic moment of the white dwarf and the magnetospheric radius is given by (Frank, King, & Raine 1992)

$$r_m = 2.8 \times 10^{10} (M/M_\odot)^{1/7} R_9^{-2/7} L_{33}^{-2/7} \mu_{33}^{4/7} \text{ cm}, \quad (4)$$

with $\mu = 10^{33} \mu_{33} \text{ G cm}^{-3}$, the accretion luminosity $L = 10^{33} L_{33} \text{ erg s}^{-1}$ and $R = 10^9 R_9 \text{ cm}$.

Hence,

$$V_{max} \sim 2.9 \times 10^{11} (M/M_\odot)^{1/7} \mu_{33}^{-3/7} R_9^{-5/7} L_{33}^{5/7} \text{ Volts}. \quad (5)$$

A related model which combines aspects of the the unipolar-inductor model and that for pulsar magnetospheres was proposed by Cheng & Ruderman (1991). They argued that as in pulsar magnetospheres, charge separation can take place in the magnetosphere and

charge depletion through the light cylinder would lead to the formation of a charge-deficient vacuum gap, provided that $\Omega_d(r_1) > \Omega$. Although the models proposed by Chanmugam & Brecher (1985) and Cheng & Ruderman (1991) differ in detail and in the location of the site of the acceleration, they are both based on Faraday's induction law applied to an accretion disk rotating in an external magnetic field. In the model of Cheng & Ruderman (1991), the acceleration of the protons takes place in the vacuum gap. Most of the potential drop occurs between the star and the disk and takes place through the vacuum gap and not across the disk. Cheng & Ruderman (1991) deduced that the maximum potential developed is

$$V_{max} \sim \frac{1}{c}(\Omega_d(r_1) - \Omega) \frac{B_s R^3}{r_1} \sim \frac{1}{c}(1 - \omega_*) \left(\frac{\Omega}{\omega_*}\right) \left(\frac{\mu}{r_m}\right), \quad (6)$$

where the fastness parameter $\omega_* = \Omega/\Omega_d$.

These mechanisms are most effective in the regions that have magnetic field strengths $B \lesssim 10^7$ G and where curvature radiation is minimized, both conditions favoring magnetic CVs. One difficulty with these models is the requirement of a low particle density ($< 10^{10}$ cm $^{-3}$) just above the disk, else the electrostatic potential will be shorted out as a result of the disk plasma present in the gap and limit the accelerating potential (Katz & Smith 1988, Kiraly & Mészáros 1988).

Lamb et al. (1992) also argue against the presence of vacuum gaps. They point out that the potential difference between the inner disk and the white dwarf is large ($\sim 10^{13}$ eV), while the gravitational potential energy holding particles in the disk is much smaller ($\sim 10^6$ eV). Even small fluctuations in the electric field near the accretion disk are sufficient to cause protons and electrons to enter the magnetosphere. Furthermore, the particle accretion rate onto the star should be $\sim 10^{40}$ particles s $^{-1}$. MHD instabilities caused by the twisting of the magnetic field can inject adequate plasma into the magnetosphere to give values much larger than those deduced from equation (1). The value of n above the

disk will easily be exceeded if even one charged particle in 10^{10} is removed from the disk. The vacuum gap model requires complete charge separation which, based upon the above estimates, appears to be unlikely. For example, X-ray observations by Becker et al. (1977) suggest a particle density of at least 10^{11} cm^{-3} , much larger than the value predicted by equation (1).

Such shorting can be avoided (Ghosh & Lamb 1991; Lamb et al. 1992) if the magnetic field is coupled to the inner part of the disk and differential rotation produces an electromotive force

$$EMF = \oint (\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B}) \cdot d\mathbf{l} \quad (7)$$

driving field-aligned currents. These currents then induce an azimuthal magnetic field (this process can be thought of as the twisting of the radial field by the differential rotation of the disk). The electrodynamics of the system creates a large current radially in the disk plane since the disk resistance is small. In this case the EMF generated is large even if the star is rotating slowly (Lamb et al. 1992)

$$\mathcal{E}_g \sim 1.210^{13} \left(\frac{r_m}{10^{10} \text{ cm}} \right)^{-5/2} \mu_{33} (M/M_\odot)^{1/2} \text{ Volts.} \quad (8)$$

Note that this result is essentially the same as that obtained in the unipolar-inductor model (c.f., equation [2]). Microscopic or magnetohydrodynamic instabilities may also develop, accelerating ions to very high energies either through the creation of double layers or via magnetic field reconnection.

In Table 1, we give the maximum voltages that can be generated, according to equation (8), in the IPs BG CMi and RE 0751+14 for which magnetic fields have been estimated, and for AE Aqr which has the fastest spinning white dwarf known. Its magnetic field is not known but, based upon the spin down measure (DeJager et al. 1994b), is estimated

to be about 1 MG. We have assumed a mass of $0.8 M_{\odot}$ for the white dwarf mass and an accretion luminosity of $L = 10^{33} \text{ erg s}^{-1}$. Note that the voltages are of order 10^{11} Volts for BG CMi and RE 0751+14 and in the TeV range for AE Aqr. This is because AE Aqr has a slightly weaker magnetic field than the other two binaries, as illustrated by the value of $r_m/R \sim 6$, so that inner edge of the accretion disk is closer to the stellar surface because r_m is lower, and as a result the magnetic field in the vicinity of the inner disk is actually higher because of the r^{-3} dependence of the stellar dipole field. The γ -ray yield efficiency is $\sim 3\text{-}10\%$ (Mitra 1991) The maximum γ -ray luminosity is hence $L_{\gamma} \lesssim 0.1L(R/r_m)$, since only a fraction R/r_m of the accretion luminosity is available at the inner edge of the disk. For a given accretion rate, the maximum γ -ray luminosity occurs for systems with relatively weak magnetic fields, such as AE Aqr, where $r_m/R \sim 6$ (see Table 1). If $L \sim 10^{33} \text{ erg s}^{-1}$, then for AE Aqr we find that $L_{\gamma} \sim 2.5 \times 10^{31} \text{ erg s}^{-1}$. If one assumes a distance of 100 pc, one expects fluxes $2 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ within the EGRET energy band of 0.1 to 10 GeV. These predicted fluxes are comparable to the EGRET threshold.

Finally, the fourth mechanism, magnetic reconnection, is expected to take place near the disk's inner edge. The result is a parallel electric field than can accelerate particles to high energies (see Tavani & Liang 1993 for details).

Any of these mechanisms can result in relativistic electrons that are necessary to explain the radio synchrotron seen from at least AE Aqr (Bastian, Dulk, & Chanmugam 1988). However, these same electrons will up-scatter the intense ultraviolet radiation field expected to be present around a CV (e.g., Kriz & Hubeny 1986). Synchrotron losses should be considerable, thereby robbing the up-scattered flux. The expected inverse Compton contribution will be less than the contributions from the mechanisms already described. Furthermore, for inverse Compton scattering to be important, it should be at least as important as synchrotron emission. Suppose that a relativistic distribution of electrons is produced by the acceleration process so that the distribution is given by

$N(\gamma)d\gamma = N_0\gamma^{-m}d\gamma$, where γ is the Lorentz factor for the electrons. Let U be the energy density of the (typically X-ray) thermal photons present in the vicinity of the inner edge of the accretion disk where $r \sim r_m$, and let T be the temperature of the photons. Then since $U = 3L/4\pi r^2 c$, the ratio of the intensity of synchrotron emission to that of inverse Compton emission is given by (see e.g., Felten & Morrison 1966)

$$\frac{I_s}{I_c} = \frac{B^2}{8\pi U} \left(\frac{2 \times 10^4 T}{B} \right)^{(3-m)/2}. \quad (9)$$

If we restrict the discussion to a most likely candidate for γ -ray emission, then assuming $L_{33} = 1$, $T = 10^5$ K, $M = 0.8M_\odot$, and $R_9 = 0.71$, we find that for the spectral index $m = 4$, $I_s/I_c = 0.01$, i.e., inverse Compton emission is more important than synchrotron emission. However, for $m = 2$, we find that $I_s/I_c = 4.4 \times 10^4$, i.e., inverse Compton emission is unimportant. If $T = 10^4$ K, similar conclusions are obtained.

Regardless of the mechanism, once particles are accelerated to sufficiently high energies γ -rays can be produced from π^0 decay products following the collision of relativistic protons with the circumstellar gas immediately surrounding the white dwarf, or by inverse Compton scattering of UV/X-ray photons by directly-accelerated electrons, or by those electrons resulting from the decay of $\pi^\pm$ produced in the proton-gas collisions (Mittra 1990). The issue becomes not whether CVs might be γ -ray sources, but, assuming a modest efficiency in the production of γ -rays, what are the resulting luminosities and can we detect CVs at the calculated values?

An important question is whether γ -ray photons can escape the disk. Stenger (1984) found that the optimum column density for production of γ -rays is ~ 50 g cm $^{-2}$. This question has been discussed recently by Bednarek (1993). He calculated the optical depth for γ -rays from a Shakura-Sunyaev (1973) accretion disk surrounding a $1M_\odot$ compact object and varied the emergent angle, the opening angle of the disk, the inner radius of the disk, and the radial size of the disk. The results indicate that photons with energy $\lesssim 1$ GeV will

escape as the optical depth is lower for disks in a weaker potential field (either farther from, or with a lower mass for, the compact object) or in a larger or cooler disk. The calculation should be re-done specifically for a CV.

3. THE OBSERVATIONS

In this section, we describe the instrument, the observations made, and the upper limits assigned. The EGRET instrument covers the 30MeV to 30GeV energy range. It is a multi-level, thin-plate, spark chamber that detects γ -rays by $e^\pm$ pair production. The energy resolution is provided by a NaI (Tl) calorimeter located below the thin-plate stack. A plastic scintillator surrounds the instrument, providing an anti-coincidence filter for non- γ -ray events. Details of the instrument have been published by Hughes *et al.* (1980), Kanbach *et al.* (1988, 1989), and Nolan *et al.* (1992). The instrument calibration is described by Thompson *et al.* (1993). In-flight performance has been described by Thompson *et al.* (1993) and Nolan *et al.* (1992).

We compiled a list of magnetic CVs, and, for completeness, novae that detonated during the *Compton Observatory's* in-orbit lifetime, novae still bright in recent X-ray observations, and a few additional nova-likes and dwarf novae. This list was processed with the EGRET point source detection software (Mattox *et al.* 1994). The data used included observations from the EGRET all-sky survey (1991 April to 1992 November). In all cases an upper limit was obtained. Tables 2-5 list the CVs included in this study. The tables are divided by CV subclass (2: DQ Her and 3: AM Her binaries; 4: novae; 5: dwarf novae and nova-likes) and ordered by increasing galactic longitude. Exposure times are listed in units of On-Axis Day (OAD) which is 3.6×10^7 cm² s for $E > 100$ MeV. Two columns of the flux upper limit exist; one corresponds to upper limits for photon energies above 100 MeV while the second lists the upper limits above 1 GeV. All fluxes are in units of 10^{-8} cm⁻² s⁻¹. The

flux upper limits are all 95% confidence level upper limits. The detection significance is included only for the 100MeV upper limits. We turn now to a discussion of the detection significance.

As the galactic γ -ray background must be modeled to place an upper limit upon the emission from a point source, we give a brief summary below of the background determination and model. Full details of the EGRET background model are given in Hunter et al. (1994). The EGRET point source analysis uses the technique of maximum likelihood (e.g., Cash 1979). The robustness of the analysis has been demonstrated with a Monte Carlo simulation of the statistics by Willis et al. (1994), who showed that ~ 1 source in the phase 1 survey could be a spurious detection above the significance limit of 16 if the diffuse galactic radiation model has no discrepancies; a significance value of 25 corresponds approximately to a 5σ detection. Upper limits depend upon the assumed background (Mattox et al. 1994). As most CVs are in the galactic plane, the background for point source analysis is the γ -ray galactic plane emission as detected by EGRET.

The diffuse emission background model used in the point source analysis is the convolution of the EGRET point spread function and the diffuse γ -ray galactic emission model of Bertsch et al. (1993). The Bertsch et al. (1993) model assumes the EGRET diffuse γ -ray photons are the result of cosmic ray interactions with matter and inverse Compton scattering. The model is the result of studies made over the past 20 years, in particular with data from SAS-2 (Fichtel et al. 1975; Hartmann et al. 1979) and COS-B (Mayer-Hasselwander et al. 1980; 1982). These observations have shown that the diffuse γ -ray emission correlates relatively well with the structural features of the Galaxy based upon surveys of atomic and molecular hydrogen.

Bertsch et al. (1993) assume specific cases of interactions of cosmic rays: nuclear interactions, electron bremsstrahlung interactions, and inverse Compton scattering. Nuclear

interactions with matter produce the greatest quantity of γ -ray photons above 70 MeV. The collisions create neutral and charged pions of which the neutral pions decay directly into two γ -rays, while the charged pions decay into e^-e^+ which annihilate, resulting in the 0.511 MeV line. Electrons interact via bremsstrahlung which dominates the nuclear component below 70 MeV. Finally, inverse Compton scattering of photons from the interstellar radiation field by energetic cosmic ray electrons can produce γ -rays.

Two primary constituents of matter are present in the interstellar medium: atomic and molecular hydrogen. Atomic hydrogen is traced directly by radio surveys. The presence and mass of molecular hydrogen must be inferred from radio observations of CO. A conversion factor is required to convert from the integrated CO intensity to the H_2 column density (factor 'X'):

$$N_{H_2}[v(i+1), v(i)] = X \int_{v(i)}^{v(i+1)} T_b(v) dv. \quad (10)$$

X is believed to lie in the range $1-4 \times 10^{20}$ molecules cm^{-2} $(\text{K km s}^{-1})^{-1}$. It is the first of two adjustable parameters in the model. The second parameter is the coupling scale of the cosmic rays to the matter. The coupling scale enters in the convolution of the surface density of the matter with a Gaussian distribution that has as a width the coupling scale. The cosmic rays are thus assumed to be related to the matter distribution smoothed by a Gaussian with a size equal to the coupling scale which is believed to be $\sim 2-3 \text{ kpc}$.

As a result of the above approach in dealing with the background, source detection becomes somewhat problematic. Strong sources will of course be detected. However, the model can over- or under-estimate the actual γ -ray galactic diffuse emission. We have used the instrument teams' analysis software in spite of the potential for over- or under-estimates. We minimized poor estimates in two ways. For the analysis in this paper, a small analysis aperture of $\sim 13^\circ$ was used. The model described above was also locally adjusted to fit the galactic diffuse emission in that region, thereby minimizing the amount

of over- and under-prediction of the galactic diffuse emission. By itself, an under-estimate of the diffuse emission is not a major concern because the lack of detections places a somewhat lower upper limit on the presence of a source than if the proper background were used. Over-estimates of the background by the model are a concern because weak sources may escape detection. We believe the upper limits reported here are the best possible, given the uncertainties in the EGRET background. A proper analysis is unlikely to change the upper limits reported here by more than $\sim 25\%$. We point out that upper limits, by the EGRET team, were carried out with the same approach on Seyfert galaxies (Lin et al. 1993), globular cluster sources (Michelson et al. 1994), and superluminal AGN (Montigny et al. 1994).

4. RESULTS

We immediately see from Tables 2-5 that no source was detected at a significance $\gtrsim 2\sigma$. Further, no CV has been identified with a detected source in the EGRET source catalog (Fichtel et al. 1994). An estimate of the upper limit on the luminosity can be obtained by calculating the average energy of the EGRET detector, assuming an E^{-2} energy spectrum, and then calculating the resulting luminosity based upon the upper limits to the fluxes. The average energy is

$$\bar{E} = \frac{\int_a^b k E^{-2} E dE}{\int_a^b k E^{-2} dE} \quad (11)$$

where a and b are the energy bounds. From Tables 2-5, we have flux upper limits at $\sim 100\text{MeV}$ and $\sim 1\text{GeV}$; the energy bounds then become $a=100\text{MeV}$, $b=30\text{GeV}$ for the $\sim 100\text{MeV}$ flux limit, and $a=1\text{GeV}$, $b=30\text{GeV}$ for the $\sim 1\text{GeV}$ limit, yielding average energies of $\sim 500\text{MeV}$ and $\sim 3\text{GeV}$. From the tables we then see upper limits of $\sim 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ and $\sim 2 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$, respectively. These upper limits translate into luminosity upper

limits of $<10^{31}$ ergs s^{-1} , assuming an average CV distance of ~ 100 pc. Since the typical CV accretion luminosity $L \sim 10^{32-34}$ ergs s^{-1} , the efficiency of production of γ -rays must be $<1\%$. Bhat et al. (1991) claimed a γ -ray luminosity for AM Her of $L_\gamma \sim 2 \times 10^{32}$ ergs s^{-1} , implying a conversion efficiency of $\sim 10\%$. We believe this result, discussed further in Barrett et al. (1994), appears incorrect if an E^{-2} spectrum is expected. We caution the reader, however, that if the system flared during the Bhat et al. observation and did not flare during the EGRET observation, such a difference in the reported luminosities could possibly arise, although a factor of 20 increase seems unlikely. The case of AE Aqr, also undetected, is discussed in De Jager et al. (1994a). AE Aqr is a puzzling source; it is also the best system for detecting γ -rays (see the estimate in Table 1). The apparent non-detection suggests that the magnetic field may be slightly stronger than the assumed 1MG. A stronger field will prevent the inner edge of the disk from existing too close to the stellar surface. From (8), the result is a lower potential and a lower predicted L_γ . De Jager et al. (1994b) have shown the magnetic field is about 1MG, based upon a measurement of the spin down of the white dwarf.

If one reverses that argument, then perhaps the novalike CVs should be γ -ray sources. The magnetic field of a novalike has never been measured as it lies below the detection capabilities presently available. It is easy to imagine, however, that a continuum exists in magnetic field strength extending from the polars down to very weak fields. Table 5 shows that the novalikes are also not detected. Finally, for the other CVs, no clear mechanism exists to produce EGRET-band γ -rays. Novae, for example, will produce γ -rays at about 1MeV from radioactive decay of material synthesized just prior or during the nova detonation (c.f. Starrfield et al. 1993 and references therein). Nova physics is not challenged by the upper limits reported here.

5. Conclusions

We note the models summarized here and tested with observations of the CVs were generally developed for accreting neutron stars in binary systems. To date, the *Compton Observatory* has detected very few such systems in spite of their abundance in the hard X-ray band; in other words, no accreting neutron star systems are identified in the EGRET catalog (Fichtel et al. 1994; Macomb & Mattox 1994). For example, Cyg X-3, admittedly not a typical system, has a spectral index in two OSSE observations of -2.2 ± 0.4 and -3.0 ± 0.1 (Matz et al. 1994). The observed flux at 0.5 MeV is $\sim 10^{-4}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$. That flux value guarantees no detection in the EGRET band if the power law is extrapolated to EGRET energies. These upper limits then suggest the models are somehow incorrect or the efficiencies of particle acceleration are much less than 1%.

These results may place the conclusions of Lamb et al. (1992) in context: large values of the EMF (equation 7) of $\sim 10^{12}$ V are present in disk-fed magnetized compact objects, provided that the white dwarf is not spinning in equilibrium ($|\dot{\Omega}| \neq 0$). However, instead of accelerating charges to TeV energies on a continuous basis, large conduction currents are driven in the small resistance magnetospheres. If this were the case, no γ -ray emission is expected in general. Only in the special condition when the magnetosphere is sufficiently tenuous (e.g., during times of low $\dot{M}$) may we expect micro-instabilities to develop leading to magnetic reconnection events. This could explain why AE Aqr is a flare-like radio synchrotron source, since the accretion rate is small (i.e., $I \Omega \dot{\Omega} \gg G M \dot{M} / R$). Reconnection events can accelerate mildly relativistic electrons. Furthermore, given that micro-instabilities have developed, it takes even more special conditions for the development of double layers. Only if double layers exist can the full potential drop ($> 10^{12}$ V) become available for the acceleration of near mono-energetic particles. This would also explain the detection of burst-like TeV γ -rays with flat spectra observed from AE Aqr by Bowden et al. (1992). Such flat spectra would be undetectable by EGRET.

In summary, we have analyzed the *Compton Observatory* EGRET data on known,

magnetic, recent novae, and a few additional CVs to search for γ -ray emission from them. None were detected. This experiment should be repeated when the next generation of γ -ray detectors is placed in orbit.

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Table 1: Estimates for the accelerating potential from selected asynchronous rotators.

	BG CMi	RE 0751+14	AE Aqr
B(MG)	4	10	0.1
P(min)	(14.1)	13.9	0.55
r_m (cm)	3.4×10^{10}	5.7×10^{10}	4.1×10^9
r_m/R	48	81	5.8
ω_*	0.22	0.1	0.21
Maximum Potential (Volts)	7×10^{11}	5×10^{11}	3×10^{13}
L_γ erg s $^{-1}$	2×10^{30}	1×10^{30}	2×10^{31}

* B is the magnetic field, P the rotation period of the white dwarf, r_m the magnetospheric radius, and ω_* the fastness parameter for accretion onto a white dwarf of mass $M = 0.8M_\odot$, radius $R = 7.1 \times 10^8$ cm and accretion luminosity of 10^{33} erg s $^{-1}$. The maximum potential is calculated using equation 8.

Table 2: Upper Limits on CVs: Asynchronous Rotators (IP or DQ Her stars)

CV Name	L	B	OAD ¹	Flux ²	100MeV	Detect. Signif.	1GeV
					Flux UL ²		Flux UL ²
V1223 Sgr	4.96	-14.36	71.53	...	6.36	0.0	1.51
AE Aqr	45.28	-24.42	63.32	...	5.72	0.0	0.01
FO Aqr	53.00	-49.16	50.83	...	4.62	0.0	1.18
V795 Her	56.66	+34.12	32.69	...	6.03	0.0	0.05
AO Psc	68.67	-53.34	46.15	...	6.75	0.6	2.30
V533 Her	69.19	+24.27	35.42	...	6.50	0.0	1.47
V1089 Peg	70.72	-30.03	47.16	...	5.83	0.0	1.44
DQ Her	73.15	+26.44	31.03	...	8.04	0.0	2.16
GK Per	150.96	-10.10	82.01	...	5.48	0.0	1.38
HV Tau	178.08	-10.31	144.39	2.90±2.69	8.41	1.0	0.71
RE0751+14	206.05	+19.79	42.62	...	5.80	0.0	0.40
BG CMi	208.48	+13.36	54.18	...	5.67	0.0	0.02
TV Col	236.79	-30.60	34.06	...	6.41	0.0	1.95
TX Col	246.77	-29.73	43.34	...	9.25	0.7	1.61
V346 Pup	247.68	-11.68	51.30	...	7.37	0.0	1.29
VZ Pyx	250.25	+13.88	51.08	...	8.31	0.7	1.25
V347 Pup	256.42	-26.55	63.11	...	7.33	0.9	1.15
TW Pic	266.42	-32.78	84.13	...	5.17	0.5	0.95
KO Vel	277.88	+7.20	69.98	...	5.95	0.0	0.99
H0616-818	293.78	-28.24	77.04	...	4.81	0.0	0.68
H0551-819	293.79	-28.20	77.00	...	4.82	0.0	0.67
EX Hya	303.19	33.62	45.39	3.55±3.31	10.70	1.1	0.50
RE1711-46	341.89	-3.96	58.82	...	16.29	0.0	2.02

¹OAD = On-Axis Day = $3.6 \times 10^7 \text{ cm}^2 \text{ s}$ for $E > 100 \text{ MeV}$

Table 3: Upper Limits on CVs: Synchronous Rotators (Polars or AM Her stars)

CV Name	L	B	OAD ¹	Flux ²	100MeV Flux	Detect.	1GeV Flux
					UL ²	Signif.	UL ²
MR Ser	31.72	+47.71	34.13	...	5.67	0.0	1.77
QQ Vul	61.53	-4.92	66.42	...	9.09	0.0	1.01
AM Her	77.86	+25.88	30.46	...	9.89	0.5	1.96
V1500 Cyg	89.82	-0.07	41.40	...	14.99	0.0	2.24
EP Dra	100.08	+23.86	29.66	...	8.46	0.0	1.97
BY Cam	151.83	+15.69	59.98	...	5.86	0.0	1.12
AN UMa	165.83	+62.15	64.98	...	3.60	0.0	0.85
ST LMi	211.80	+66.21	47.09	...	6.48	0.7	1.94
EF Eri	212.94	-57.41	37.33	...	8.30	0.8	1.01
UZ For	220.31	-53.41	37.12	...	5.49	0.0	1.28
EX0332-25	220.41	-54.21	38.63	...	4.77	0.0	1.50
DP Leo	230.90	+66.46	46.98	4.04±2.51	9.49	1.6	1.66
VV Pup	239.65	+8.71	44.53	...	6.36	0.0	1.83
1E0830-22	245.19	+10.10	47.63	...	12.31	1.5	1.35
RE0531-46	252.58	-32.67	52.96	6.17±3.15	12.84	0.0	1.76
WW Hor	272.23	-58.11	57.28	...	8.08	0.8	1.34
BL Hyi	295.92	-48.56	66.96	...	3.98	0.0	0.81
V834 Cen	316.98	+15.45	49.89	...	7.58	0.0	1.85
RE1938-46	352.45	-27.07	39.74	...	7.56	2.0	0.05
CE Gru	356.70	-47.94	26.68	7.30±4.45	16.93	1.7	0.10

¹OAD = On-Axis Day = $3.6 \times 10^7 \text{ cm}^2 \text{ s}$ for $E > 100 \text{ MeV}$

²Units = $10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$.

Table 4: Upper Limits on CVs: Novae

				100MeV		1GeV	
CV				Flux	Detect.	Flux	
Name	L	B	OAD ¹	Flux ²	UL ²	Signif.	UL ²
V849 Sgr	0.20	-6.97	78.66	...	8.69	0.0	0.87
V1148 Sgr	5.32	-3.07	84.02	...	13.04	0.0	1.05
V553 Oph	7.24	+5.09	83.70	...	15.47	0.7	...
MU Ser	14.07	+5.55	79.92	...	11.14	0.0	1.91
GL Sct	25.01	-2.85	88.16	...	11.73	0.0	1.15
GL Her	43.32	+6.62	68.07	...	10.70	0.3	1.12
V1974 Cyg	89.40	+7.74	66.42	...	10.09	0.0	3.09
V351 Pup	252.72	-0.73	63.94	...	9.40	0.0	0.97
CP Pup	252.93	-0.84	63.94	...	9.56	0.0	1.08
V442 Mus	295.30	-7.07	58.64	...	9.11	0.1	1.08
GQ Mus	297.21	-5.00	54.11	...	9.78	0.0	...
HS Cen	309.51	-1.03	41.36	...	21.01	0.0	3.48
V842 Cen	316.57	+2.45	44.03	14.21±8.16	30.96	1.7	2.48
V341 Nor	330.42	-1.61	94.14	...	19.20	0.0	3.60
GW Lib	340.71	+26.77	47.16	...	7.57	0.2	1.36
V2214 Oph	355.38	+5.72	80.64	7.62±5.08	17.99	1.5	2.07
V977 Sco	357.60	-3.00	80.68	...	13.60	0.0	3.64
V825 Oph	358.78	+5.86	83.70	10.02±5.25	20.69	1.9	1.57

¹OAD = On-Axis Day = $3.6 \times 10^7 \text{ cm}^2 \text{ s}$ for $E > 100 \text{ MeV}$

²Units = $10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$.

Table 5: Upper Limits on CVs: Miscellaneous CVs

CV Name	L	B	OAD ¹	Flux ²	100MeV	Detect.	1GeV
					Flux UL ²	Signif.	Flux UL ²
Dwarf Novae							
SS Cyg	90.56	-7.11	38.02	...	6.23	0.4	1.90
U Gem	199.22	+23.39	43.63	...	16.25	0.5	2.04
VW Hyi	284.89	-38.13	89.74	...	3.65	0.1	...
V426 Oph	33.24	+12.35	56.77	...	8.05	0.0	1.20
SW UMa	164.82	+36.96	50.69	2.63±2.60	8.26	1.0	...
CP Eri	191.70	-52.91	42.55	...	5.35	0.0	...
AH Eri	208.31	-38.97	42.40	3.52±3.04	10.12	1.2	0.55
AL Com	282.86	+76.47	75.20	...	5.02	0.6	1.09
HV Vir	319.88	+63.78	76.36	...	3.54	0.0	1.11
V2051 Oph	358.01	+8.62	81.40	...	8.39	0.0	1.52
Novalikes							
UX UMa	107.03	+63.40	53.07	...	6.23	0.4	1.90
RW Tri	147.02	-30.33	45.75	...	6.21	0.1	1.90
SW Sex	245.52	+41.68	28.40	3.75±3.81	11.92	1.1	0.60
V3885 Sgr	357.48	-27.76	43.27	...	11.36	0.6	...
IX Vel	264.93	-7.89	88.68	...	9.75	0.2	...
SX LMi	199.34	+64.24	50.44	...	5.42	0.5	1.83

¹OAD = On-Axis Day, units = $3.6 \times 10^7 \text{ cm}^2 \text{ s}$ for $E > 100 \text{ MeV}$

²Units = $10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$.