Bull Astr Soc India (1990) 18, 215-227

Gamma ray observations of polars

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Abstract. We present here evidence based on data from three independent experiments which suggests that polars constitute an important and hitherto unknown class of gamma-ray sources with photon energies possibly extending upto PeV energies. An outstanding feature of the observed gamma-ray light curves is the striking morphological similarity that they exhibit with the corresponding phase dependence of the circularly polarized light from these objects.

Key words : polars—γ-rays—binaries

1. Introduction

Polars are a subclass of cataclysmic variable binary systems comprising a synchronously-rotating magnetic white dwarf accreting matter from a Roche lobe-filling, late-type, main sequence star (Chiapetti *et al.* 1980; Liebert & Stockman 1983). The strong magnetic field of the primary ($\sim 10^7$ gauss) does not allow the formation of an accretion disc in these objects but, instead, channels the accreting matter to one or both polar caps of the degenerate star. This causes the formation of a standing shock wave near the accretion zone(s) and also leads to phase-modulated emissions in various wavelength regimes, including that of polarized light via the cyclotron process.

Around 10 such systems are known today (Patterson 1984), the prototype being AM Herculis, situated 75 pc away and having a binary period of 3.1 hr. These systems have till recently been studied only up to x-ray wavelengths What motivated us to examine them for possible emission at gamma-ray energies was a hint of a signal from AM Herculis above 0.5 PeV energies (1 PeV = 10^{15} eV) following an epoch-folding analysis of atmospheric Cerenkov data collected in mid-seventies at Gulmarg Accordingly, the recently commissioned TeV gamma-ray telescope at Gulmarg was made to collect data in the direction of AM Her for ~ 83 hr in tracking and on-off modes. An analysis of the recorded data clearly indicates the presence of a statistically significant phase-modulated signal from the source, corresponding to an integral flux of $(5.6 \pm 2.1) \times 10^{-11}\ \gamma\ \mathrm{cm^{-2}\ s^{-1}}$ at gamma-ray energies > 2 TeV. What provides a measure of confirmation to the Gulmarg results is the possible detection of two other polars E 1405-451 and VV Pup at photon energies > 50 MeV from the COS-B satellite database. (Unfortunately, neither

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this experiment nor its American forerunner, SAS-2 has had any worthwhile exposure in the direction AM Her itself). As observed in the case of the prototype object AM Her, the gamma-ray light curves of these COS-B sources also exhibit an impressive correlation with the corresponding phase-dependence of the circularly polarized light detected from the sources.

2. Experimental details

The PeV data analysed here belong to the two-year period 1976 January-1977 December and were recorded at Gulmarg by two coincidently-operating, large-area photomultipliers (EMI 9545 B) exposed to the night sky in a geometrical field of semi-angle $\sim 70°$. The average Cerenkov event rate is ~ 1 min^{-1} and the corresponding threshold energy for primary gamma-rays ~ 0.5 PeV. For additional information, see Bhat *et al.* (1986), where evidence is also presented from this experiment for possible detection of a phase-modulated flux of gamma-rays from the well-known x-ray system Cyg X-3.

The TeV data on AM Her were collected by one bank of the Gulmarg gamma-ray telescope (Koul *et al.* 1989). The bank comprises three, 0.9 m-aperture parabolic mirrors which are provided with a synchronous-movement control. Observations were carried out between 1987 April-July in the tracking mode and between 1987 September-October in the on-off mode. Three-fold prompt and chance or delayed coincidence rates (PCR and DCR respectively) were recorded alongwith the corresponding absolute time-information, using a sampling time of 279s (= 1/40th of the source period). A padding lamp-based background compensation circuit was used to keep the ambient light level steady during observations. A genuine coincidence rate (GCR = PCR − DCR) of 1 Hz from the zenith direction was realized during observations, which corresponds to a threshold energy of 2 TeV for the primary gamma-rays.

The data on E 1405-451 and VV Pup correspond to the photon energy band 50-5000 MeV and have been collected by the COS-B satellite. The exposure factor for either source is rather low, averaging to $\sim 8 \times 10^7$ cm^2 s, but what permits us to proceed with this investigation meaningfully is that both the sources fortuitously lie away from the rather intense gamma-ray background of the galactic plane.

3. Data analysis and results

3.1. *PeV energies*

Using the ephemeris of Priedhorsky *et al.* (1977), the arrival times of events recorded by the wide-angle Cerenkov system have been folded with the AM Her orbital period of 3.1 hr. Figure 1a shows the on-source phasogram comprising events recorded when AM Her was at a zenith distance $< 40°$, while figure 1b gives the coresponding off-source phasogram ($\psi > 70°$). The sample mean level (70.8 ± 1.1) h^{-1} in figure 1a is significantly higher than that of (58.1 ± 0.8) h^{-1} in figure 1b and is most probably due to possible changes in the system operational parameters during the interval of several months separating the two observation spells. A more reliable estimate of the background level results by considering the more contemporaneous data collected when AM Her was at $40° < \psi > 70°$. The resulting value of (69.9 ± 1.8) h^{-1} is reassuringly in excellent agreement with the above referred on-source sample average level and is shown by the dotted line in figure 1a. A comparison of the two phasograms (figure 1a and 1b) now

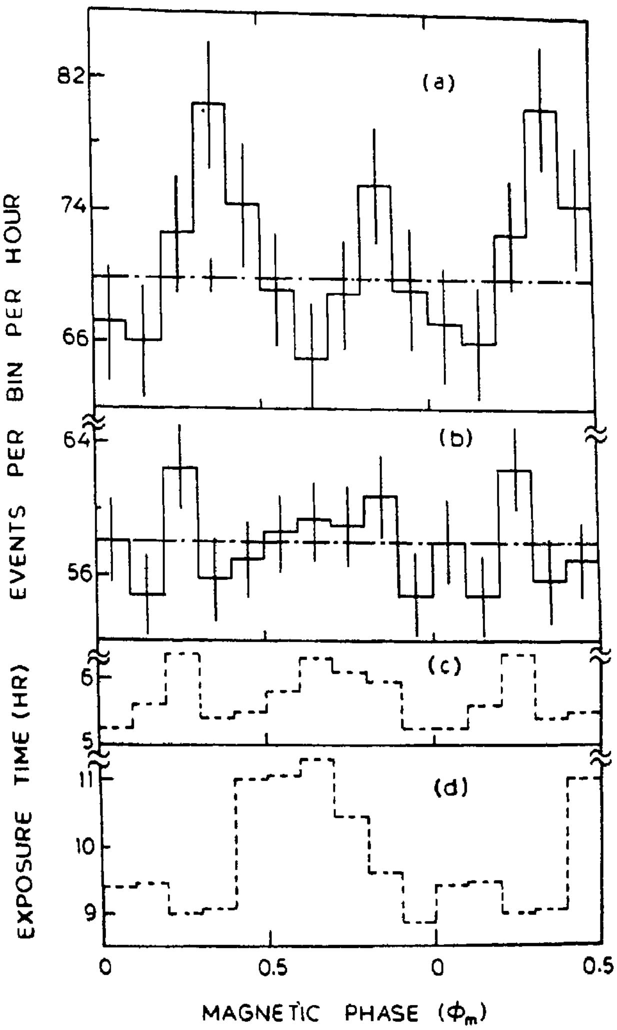

Figure 1. On-and off-source phasograms obtained by the epoch-folding analysis of atmospheric Cerenkov data recorded when AM Her was at a zenith angle $\psi < 40°$(a) and $\psi > 70°$ (b) respectively. (c) and (d) give the actual exposure time for various phase bins of the on- and off-phasograms. – – – : cosmic ray back-ground level

reveals a noticeable departure from the expected distribution (inferred from respective sample-average levels and the exposure time per bin) only in the case of the on-source phasogram. This is characterized by a reduced χ^2 of ~ 2 as against a value of ~ 1 in the case of the off-source phasogram. Considering only the moderately significant positive excursion (~ 3σ) at the magnetic phase ϕ_m ~ 0.3 in figure 1a, we find 11 events observed over and above the number expected on the basis of the background level of 69.9 events h^{-1} and the exposure time for $\phi_m = 0.3$. If these excess events are assumed to be gamma-rays from AM Her, we obtain a source flux of $(2.5 \pm 1.0) \times 10^{-13}$ cm^{-2} s^{-1} at photon energies $E_\gamma > 0.5$ PeV.

3.2. *TeV energies*

This work is discussed in detail in Bhat *et al.* (1991) and we present here only the salient features. Around 50 hours of TeV data, obtained in the tracking mode in the direction of AM Her, were subjected to a phase-histogram analysis using the above-mentioned ephemeris. In the present case, the start of each 279 s interval in the observations on a given day was assigned a heliocentric phase value with respect to this object. Figure 2a represents the resulting on-source phasogram, while figures 2b and 2c respectively show the time coverage of various phase bins and the corresponding phasogram for chance

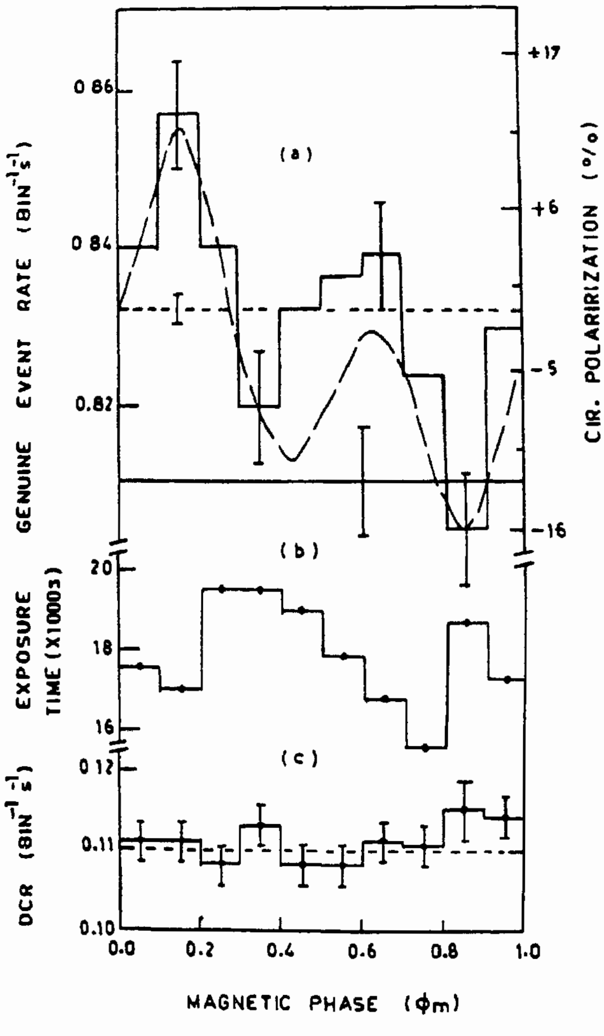

Figure 2a. TeV gamma-ray light curve of AM Her obtained by folding 16 days of on-source data. The dotted line gives the sample-average level and the full line the actual cosmic-ray background level as inferred from measurements taken in the on-off mode. The dashed line curve superimposed on the on-source phasogram is the circular polarization curve of AM Her in the V-band

Figure 2b. Exposure time in seconds achieved for different phase bins during the 16 observation days.

Figure 2c. The phasogram of chance-event rates events. Unlike in figure 1c, a significant long-term trend is apparent in figure 1a (reduced $\chi^2 \sim 3.5$ relative to the expected counts based on the sample mean level and the exposure time per bin), which includes a 3.2σ peak at $\phi_m = 0.1$ and a 3.3σ dip at $\phi_m = 0.8$. No similar trend is evident in figure 2b, suggesting that the observed modulation is not due to any exposure bias and is most probably due to gamma-rays from AM Her. Observations made in the on-off mode for 33.5 hr yield an average on-source to background-event ratio of (1.026 ± 0.008) to be compared with a value of (0.98 ± 0.02) for the corresponding chance counts. This implies an excess of $(2.6 \pm 0.8)\%$ events coming on average from AM Her and, when considered in relation to the sample average level (0.832 ± 0.0002) bin^{-1} s^{-1} (dotted line in figure 2a), yields a true background level of (0.811 ± 0.00007) bin^{-1} s^{-1} (full line). An examination of figure 2a now reveals two broad peak structures centred at $\phi_m \sim 0.1$ and ~ 0.6, with statistical significance of $\sim 4.6\sigma$ and $\sim 2.9\sigma$ respectively. The corresponding phase-averaged flux turns out to be $(5.6 \pm 2.1) \times 10^{-11}$ photons cm^{-2} s^{-1} and the source luminosity 2×10^{32} ergs s^{-1} for $E_\gamma > 2$ TeV (assuming isotropic emission).

The implied differential fluxes at TeV and PeV energies are shown in figure 3 along with the corresponding values for AM Her at lower frequencies. It is reassuring to note that, as with other known gamma-ray sources, all the plotted values, are consistent with a power law energy spectrum with an exponent of ~ -1. This spectrum suggests a value of 1-2 f.u. for the brightness of AM Her at $E_\gamma > 100$ MeV (1 f.u. $= 10^{-6}$ photons cm^{-2} s^{-1}). A

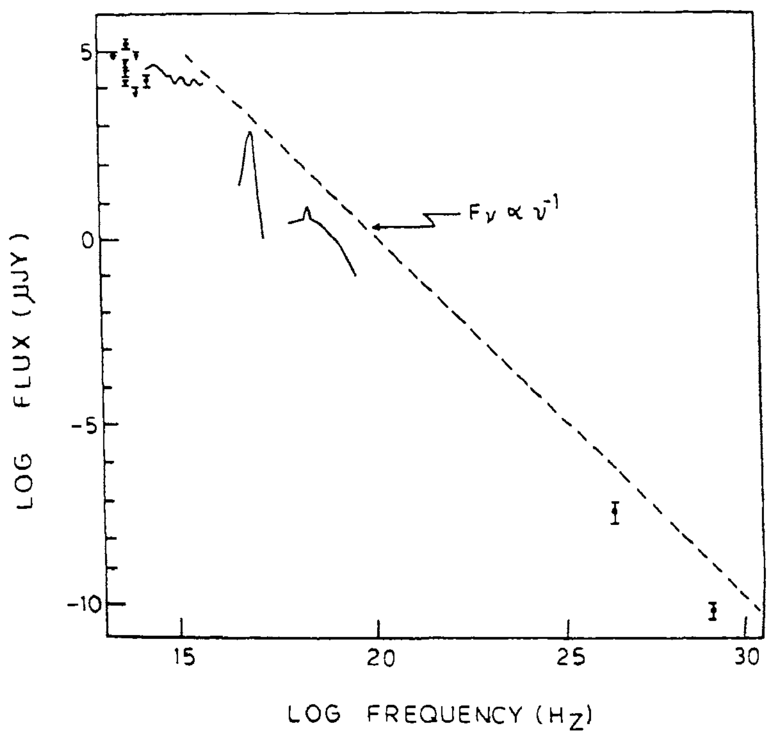

Figure 3. Differential energy flux spectrum of AM Her between infra-red and PeV gamma-ray wavelengths The non-gamma-ray data are taken from Liebert and Stockman (1983) and correspond to the source in 'high state'.

plausible reason for the apparent omission of this object from the COS-B catalogue of gamma-ray sources (threshold flux ~ 1 f.u.) is the fact that the COS-B experiment has had no sky exposure in the source direction (Bloeman 1985).

A remarkable feature of the TeV gamma-ray light curve is its striking morphological similarity with the circular polarization curve of AM Her (dashed line in figure 2a; Piirola *et al.* 1987) quantified by a correlation coefficient $r \sim 0.9$, corresponding to a confidence level > 99%. Likewise, the PeV gamma-ray light curve (figure 1a) also shows a moderately significant anti-correlation ($r \sim 0.65$) with both the circular polarization curve and the TeV light curve (figure 4). Quite interestingly, on the contrary, these gamma-ray light curves do not show any overall bin-to-bin morphological similarity ($r \sim 20\%$) with the phase modulation of the unpolarized light from the source as well as with its x-ray light curve (Chiapetti *et al.* 1980). It is most likely that the TeV and PeV gamma-rays are produced in the system by the electron-synchrotron process.

The morphological similarity between TeV gamma-rays and the phase dependence of circularly polarized (CP) light can be understood if the TeV ray source in this system is associated with the pole (region) emitting positive CP light. On the other hand, the magnetic field configuration may be such that still higher energy particles (electrons ?),

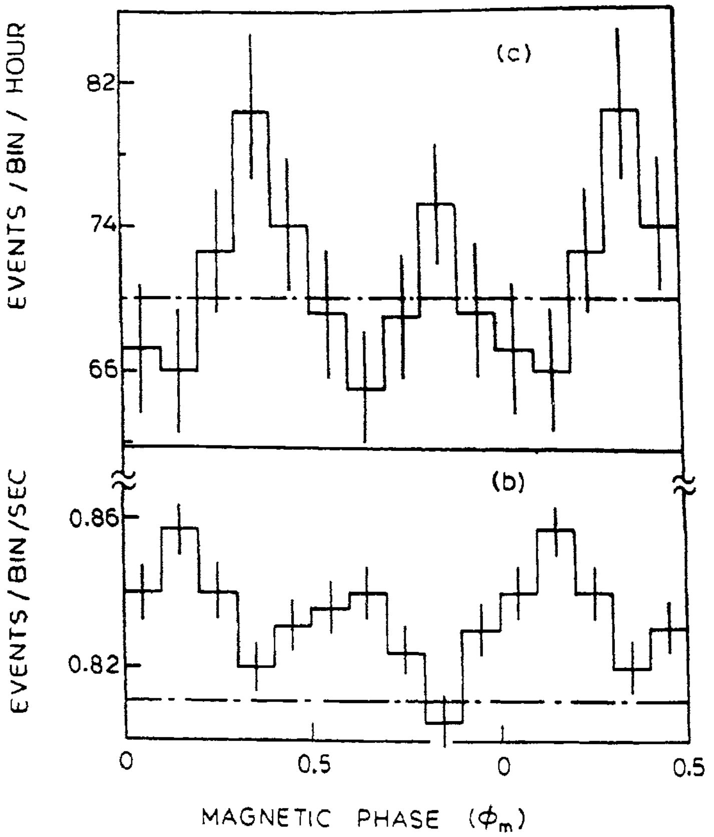

Figure 4. PeV (a) and TeV (b) γ-ray light curves of AM Herculis are compared to bring out the marked anticorrelation present in their overall morphologies

responsible for producing PeV rays, are largely confined to a different spatial region near the polar cap of the degenerate star and this leads to the dichotomic behaviour apparent in figure 4 (See Bohm-Vitense, 1967 for a review of an analogous situation found in peculiar A stars)

3 3 *MeV energies*

We now proceed on to discuss the results obtained on the two Am Her candidates. E 1405-451 and VV Pup, in the course of analysis of the COS-B database (see Bhat *et al* 1989 b for more details) The diffuse gamma-ray background contribution was kept within a manageable level by limiting the on-source' region to a circle of 4° radius centred on the candidate source. As shown by Buccheri *et al* (1983), further optimization of the signal-to-noise ratio is possible for periodic sources by appealing to the energy dependence of the instrumental point-spread function (PSF) and excluding from the phase analysis those events with energy E_γ (MeV) and angular distance from the source $> \theta_m$, where

$$\theta_m = 12.5 \ E_\gamma^{-0.16} \text{ degrees} \qquad \ldots (1)$$

Accordingly, the on-source data for E 1405-451, satisfying equation (1) were folded with the source orbital period of 1.692 h after correcting the arrival time of each event to the

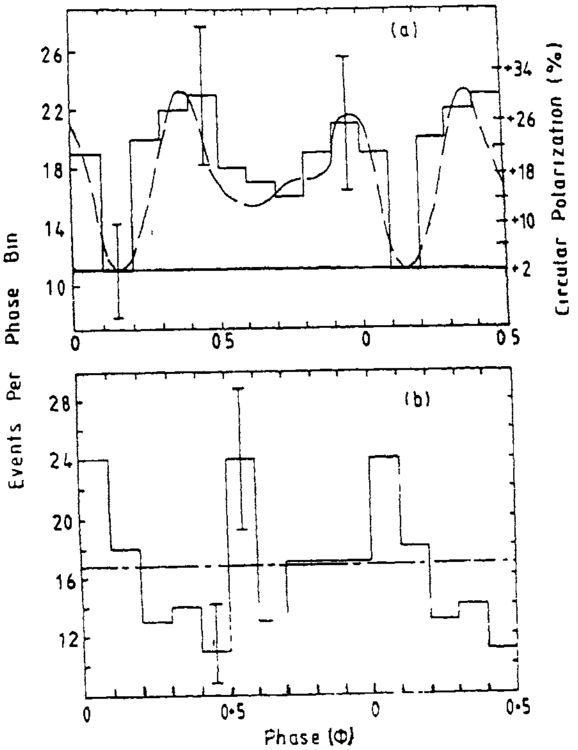

Figure 5a. Gamma-ray curve of E 1405-451 compared with the phase distribution of circularly polarized (CP) light from the source in the V-band The full-line gives an estimate of the background level
Figure 5b. The phase distribution of a sample of background gamma-rays using the E 1405-451 ephemeris The dot-dash line gives the sample average level

solar system barycentre (Mayer Hasselwander 1985). The source ephemeris is that of Mason *et al.* (1983). Figure 5a shows the resulting on-source phasogram composed of 186 gamma-rays. We have superimposed on it the phase dependence of the V-band CP light from E 1405-451 (Bailey *et al.* 1983) after normalizing at $\phi = 0.1$ and making the two curves equal in area. An excellent correlation is evident between the on-source phasogram and the CP light-curve, quantified by $r = 0.82$ and a confidence level $> 99\%$. In figure 5b, we show for comparison an 'off-source' phasogram; here the basic data, treated exactly as in the on-source case, are drawn from the concentric annulus of equal area contiguous to the on-source circle. This choice of background has the advantage of being largely free of exposure biases and is not likely to be affected by the large-scale (tens of degrees) non-uniformity present in the difuse gamma-ray background. (As will be discussed later, this choice has some drawbacks too.) Though the number of photons (168 γ's) is similar to the on-source case, the off-source phasogram (figure 5b) has no significant correlation with the CP data of E 1405-451 ($r = 0.16$ with a comparable expected error).

Figure 6a illustrates the corresponding situation for VV Pup (period = 1.674 h), based on Walker's ephemeris (Warner & Nather 1972). Once again, the areas under the on-source phasogram and the V-band CP light curve (Cropper & Warner 1986; Pirola, 1987) have been made equal and the curves have been normalized at $\phi = 0.8$. It is evident that the on-source phasogram closely matches the nearly rectangular shape of the CP light curve, including when the polarization state flips from one handedness to the other. This change in the polarization of the CP light curve is a consequence of the 'two-active poles' configuration displayed by the degenerate star in VV Pup. The geometry of the system is such that only one pole is visible at a given time while the other emitting region undergoes a sudden deep eclipse. As is seen in figure 6a, this leads to the detection of CP light of one sign between $\phi = 0.2$-0.7 ($-$ve) and of the opposite sign (+ve) between $\phi = 0.8$-0.1. The overall morphological similarity between the CP curve and the on-source phasogram yields $r \sim 0.52$ with a modest confidence level of $\sim 90\%$, most likely because the number of photons involved here is only half that of figure 5a. The off-source phasogram in figure 6b (78 photons), belonging to the equal-area annulus centred on VV Pup, displays bin-to-bin fluctuations of less than 1 σ amplitude with respect to the sample mean level (dash-dot line). When compared with the CP light curve of VV Pup, the off-source phasogram yields a much less significant $r = 0.35$.

As seen above, the on-source phasograms of E 1405-451 and VV Pup both closely follow the phase behaviour of CP light from the two candidates source, and this is reminiscent of an analogous trend exhibited by TeV gamma-rays from the prototype source AM Her. It is significant that, though the three CP light curves are quite different in their phase distribution, the same structure is consistently seen in the corresponding gamma-ray on-source data when a proper choice of ephemeris is made. This suggests that the (correlated) shape of the on-source phasogram is caused by a gamma-ray source which is physically associated with the polar cap region(s) of the white dwarf that produces the polarized light. Both CP and gamma-ray emissions experience the same aspect effects as a result of binary motion. It follows under this hypothesis that the phase distribution of CP light monitors the spatial/angular extent of the gamma-ray source that is visible and can give a measure of the fraction of source photons likely to be received in various phase bins. Thus, in E 1405-451, which, is known to have only one

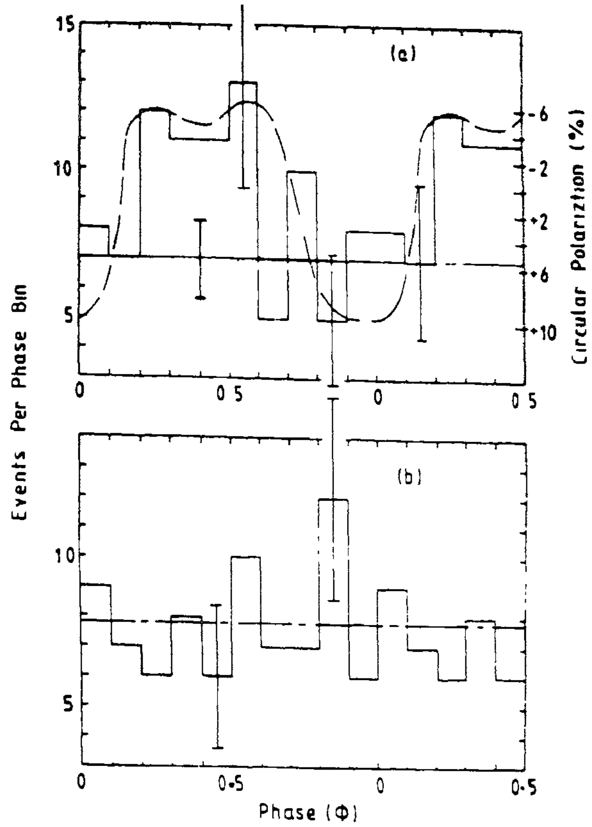

Figure 6a. Gamma-ray light curve of VV Pup compared with the circular polarization data of the source in the V-band The full-line gives an estimate of the background level Note that the polarization data have been plotted with a reversed scale (negative upwards) to emphasize that negative polarization only refers to the handedness of the polarized light and the observed correlation is not mistaken for an anti-correlation
Figure 6b. Same as in figure 5b but for VV Pup

active pole visible (Mason *et al.* 1983), the main peak in the CP light occurs at $\phi \sim 0.2$-0.4 (figure 5a), implying that most of the gamma-rays from the source should be received in this phase regions, as is indeed the case. Similarly, the CP light briefly dips to zero intensity at $\phi \sim 0.1$, indicating that the gamma-ray source in E 1405-451 should be obscured at this phase value. This is borne out by the narrow dip feature in the on-source phasogram at $\phi \sim 0.1$. On the other hand, the correlation in figure 6a can be understood in the same manner provided we further assume that the gamma-ray source in VV Pup is associated with only one active pole of the degenerate star, viz., the one that emits CP light of $-$ve polarity. This pole is in full view between $\phi = 0.2$-0.7 (as indicated by the flat-topped peak in negative CP) and so is the associated gamma-ray source, leading to the observed high state of the on-source phasogram in figure 6a. For $\phi = 0.8$-0.1, the $-$ve pole (and the associated gamma-ray source) is completely blocked from view since the maximum intensity of +vely polarized light is received during this phase interval. As the second pole is assumed to have no gamma-ray source associated with it, the on-source phasogram descends to a low state, thus explaining the shape of the on-source phasogram (and the rationale for using $\phi = 0.8$ for normalization in figure 6a).

Having thus shown that the modulations in figure 5a and 6a could be of source origin, we will now go on to retrieve the underlying signal and assess its statistical significance. We need an estimate of the gamma-ray background level for this purpose. One seemingly simple way is to derive it from the off-source annulus counts, but, in practice, this is not found to be as straightforward on account of significant uncertainties introduced here by differences in average gas column densities between the two regions and the effect of equation (1), leading to a proportionally higher fraction of background events being excluded from the annulus than from the on-source circle. Also, there may be a significant variation in the effective exposures between the two regions and it is no simple matter to take proper account of the isotropic background contribution in the case of the off-source annulus. We shall, therefore, derive the background level by the standard method of referring to a baseline feature in the light curve itself. For E 1405-451, it is the pronounced narrow dip at $\phi = 0.1$ (figure 5a), which is coincident with a similar feature in the CP light curve and as already discussed, suggests that the gamma-ray source in E 1405-451 is momentarily blocked from view in this phase bin. This yields a background level of (11 ± 3.3) photons bin^{-1}, corresponding to a total of (110 ± 10.4) gamma-rays expected as against (186 ± 13.6) events actually detected. This implies a $\sim 4.4\ \sigma$ excess from the direction of E 1405-451 with a nominal random expectation probability of 2.5×10^{-5}.

In the case of VV Pup, the low-lying section of the light curve between $\phi = 0.8$-0.1 again provides a natural baseline which is also consistent with the view that the gamma-ray source in VV Pup, associated with the pole emitting CP light of negative polarity, is obscured during this phase interval. This leads to a background value of (7 ± 1.3) photons bin^{-1}, equivalent to a total of (70 ± 4.1) gamma-rays expected in comparison to (90 ± 9.5) gamma-rays actually observed from the on-source region. This excess of 20 photons has a modest significance of $\sim 2\sigma$ corresponding to a random expectation probability of 5.4×10^{-2}.

Based on the good correlations apparent in figures 5a and 6a and the nominally good statistical significance of the phase-averaged excesses, we conclude that there is some evidence that phase-modulated signals have been detected from the two polars at gamma-rays energies > 50 MeV with a duty cycle of $\sim 90\%$ (E 1405-451) and $\sim 60\%$ (VV Pup). Turning to the flux associated with these signals, calculations yield 0.3 f.u. above 100 MeV. The corresponding gamma-ray luminosity is $\sim 10^{32}$ erg s^{-1} for a typical source distance of 100 pc and assuming isotropic emission. While the low flux level probably explains why the two objects were missed is earlier generaly surveys for point sources (Hermsen 11980), the luminosity estimate obtained above is reassuringly well within the total energy budget of the systems ($> 10\%$).

In figure 7, we compare the gamma-ray ($\mathcal{L}_\gamma$) and x-ray ($\mathcal{L}_x$) luminosities of the three AM Her objects detected so far with the corresponding quantities for the other, more secure identifications. Despite the small sample size involved, it is encouraging to note a similar increasing trend between $\mathcal{L}_\gamma$ and $\mathcal{L}_x$ for all the sources, and this adds some further weight to the suggestion made above about the AM Her sources' also being gamma-ray emitters.

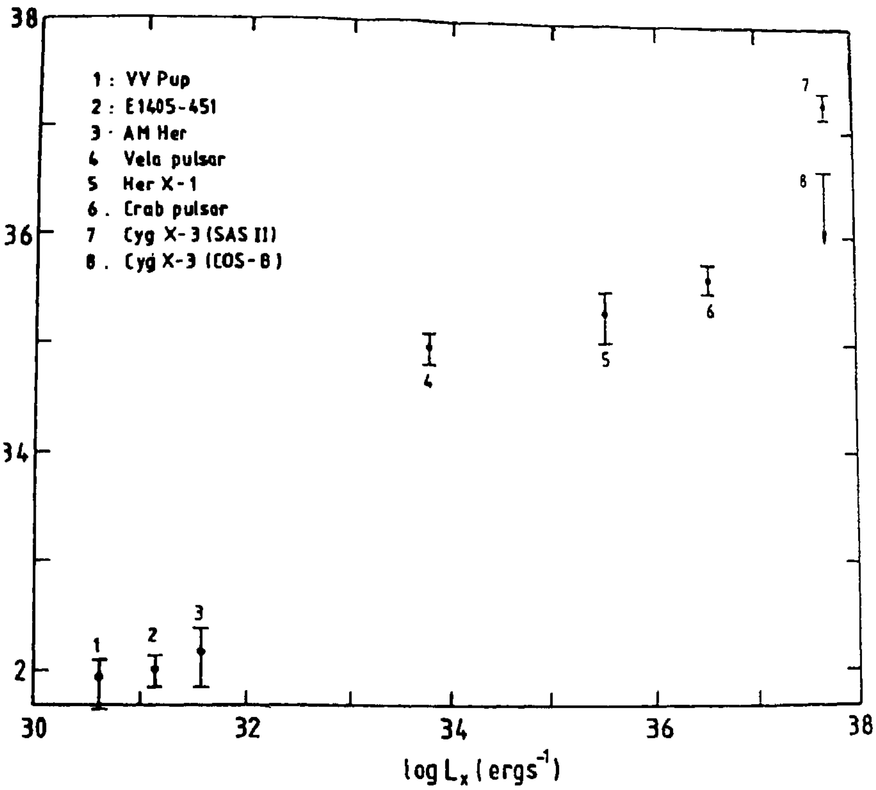

Figure 7. Gamma-ray luminosity above 100 MeV for three polars compared with the corresponding x-ray luminosity between 2-10 keV in relation to four well-known x-ray and gamma-ray sources. A thousand-fold jump is indicated in $\mathcal{L}_\gamma$ for $\mathcal{L}_x > 10^{34}$ erg s^{-1}, possibly due to 5-6 orders of magnitude difference in the magnetic field strengths of the white dwarf and neutron star compact objects which are involved in these two source populations.

4. Conclusions

An entirely new class of gamma-ray binary objects, involving a magnetic white dwarf rather than a neutron star degenerate primary, appears to have been discovered. It is imperative that these results are verified through other ground-based experiments as also by making systematic searches of the existing COS-B and SAS-II satellite databases as well as by making new observations on cataclysmic variable sources with future satellite missions like Gamma Ray Observatory and Gamma-I. If they are confirmed, the results will have important consequences for the physics underlying acceleration of high energy particle beams in binary systems (with/without accretion discs) as well as for the contribution of unresolved point sources in the galactic gamma-ray background. A fascinating possibility that offers itself involves first possible detection of extra-solar neutrons in case these relatively closeby objects indeed accelerate nucleons to PeV energies. Detailed models will also need to be worked out to explain, amongst other things, the morphological similarity between gamma-ray and circular polarization curves of these systems.

Acknowledgements

It is a great pleasure to thank my colleagues Drs H. Razdan and R. K. Kaul, and Messers H. S Rawat, V K Senecha, R. C Rannot, M. L. Sapru, A. K. Tickoo, I. K. Kaul and S. K Kaul, who have contributed substantially to the results on AM Herculis presented here Thanks are also due to Prof. A. W. Wolfendale and Dr K. M. Richardson of the University of Durham, U.K., for the all-round help culminating in the results presented here on the COS-B satellite counterparts of AM Her sources, Prof. K. D Abhyankar has evinced great interest in this work and it is a matter of great privilege to dedicate it to him on the occasion of his 60th birthday. Finally, I would like to express my gratitude to Prof M. B K. Sarma and Dr G. C. Kilambi and other organizers of the Hyderabad workshop for making it possible for me to give this talk.

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Discussion

Venugopal : The circular polarization indicates structured magnetic field. The correlation seen between TeV light curve and circular polarization suggests magnetic phenomenon. The field of 10^7 gauss warrants particles with high relativistic energies if emission is due to synchrotron process. How are they accelerated ? Why emission from only one pole?
Bhat : Shock waves (Fermi process), inverse Crompton may contribute to accelerating progenitor electrons to the energies of at least few times 10^{12} eV, required to produce TeV photons through synchrotron mechanism in a magnetic field of $\approx 10^7$ gauss.

That the TeV gamma-ray source in AM Her should be associated only with the pole producing circularly polarized light of '+ ve handedness' is suggested by experimental data themselves, *i.e.* a comparision of the circular polarization curve with the TeV gamma-ray light curve. Such a 'tentative' explanation also holds for VV Pup, for example, where the gamma-ray source is apparently associated with the polar cap region producing circularly polarized light of —ve handedness only.

Shukre : Synchrotron mechanism for these gamma rays would require very high energy particles for the low fields which occur in this case. Where do the particles get the energy?
Bhat : For a magnetic field strength of $\approx 2 \times 10^7$ gauss, measured close to the magnetic dwarf surface in the AM Her system, the particle (electron) energy needed to produce TeV gamma-rays is surely large, at least a few TeV. I would like to think that the shock waves, which are known to be formed close to where the matter gets accreted, are responsible for transporting electrons to these ultra-relativistic energies.
Shukre : Is there any physical reason as to why the gamma to x-ray outputs in these cases should show any connection to those for pulsars?
Bhat : Intuitively, we would expect gamma-ray luminosity to scale with x-ray luminosity for both the types of systems involving a neutron star or a white dwarf as a degenerate object.