Optical Pulsations of HZ Herculis

On April 15.3 (UT), we attempted to detect optical variations in HZ Herculis corresponding to its 1.2 s X-ray pulsation period. No such variations were observed to a limiting magnitude of 23.5 (modulation 0.01%).

The instrumentation used was a conventional EMI 6256B phototube with a computerized pulse counting system. Three hour-long sets of data were taken in white light with the Steward Observatory 229-cm telescope. An integration time of 13 ms was used. The data were analysed using a Cooley–Tukey fast Fourier transform routine. A frequency resolution of 3×10^{-4} Hz was obtained over the range 0.7 to 0.9 Hz.

Observations were planned for April 13 to 15 so as to cover the beginning of the "off phase" of the 35 d X-ray modulation cycle. In this manner we hoped to demonstrate that the optical pulsations (observed by Groth *et al.*[1] during the "on phase" April 6 to 7) terminate simultaneously with the X-ray pulsations. Observations were obtained only on April 15, which was probably during the "off phase".

We propose that the observed optical pulses come to us directly from the X-ray source and are merely the low frequency tail of the X-ray spectrum. Our observations, combined with those of Groth *et al.*, are consistent with this hypothesis. Furthermore, if the pulses were echoes of the X-ray source emitted by the atmosphere of the primary, we would not expect the pulses to have the strength (0.1 to 0.2%) observed by Groth *et al.*[1]. The pulses would be reduced by a factor of 10 by both light travel time across the primary and the atmospheric leak time ($\sim$100 s, ref. 2).

J. S. Scott and P. A. Strittmatter (to be published) have suggested that the X rays are produced by interaction between free-falling protons and electrons expelled from the surface of the X-ray pulsar. A similar suggestion was proposed by Cocke[3] to explain the high energy γ rays from the Crab pulsar. Such a mechanism predicts a spectrum that is flat from soft X rays to the visual, that is, that the flux density in erg cm^{-2} s^{-1} Hz^{-1} is constant.

Using emission region magnetic fields of 10^{12} gauss, electron densities of 10^{21} cm^{-3}, electron–proton interaction velocities of $V=10^{10}$ cm s^{-1} and a path length of 10^6 cm, as suggested by Scott and Strittmatter, together with a free-free absorption coefficient corrected for intense magnetic fields[4]

$$\kappa_{ff}=6.7\times10^{-18}(\lambda^3 n_e^2/V)(2\pi m_e/eB\lambda)^2$$

we predict a low frequency turnover at about 1 µm. Observational studies based on this prediction are in progress.

Taking an X-ray flux[5] of 0.08 photons cm^{-2} s^{-1} keV^{-1} at 10 keV, we compared the flat extrapolation of the spectrum converted to erg cm^{-2} s^{-1} Hz^{-1} with typical quarter phase *UBV* observations of HZ Her taken at Steward Observatory, and crudely corrected for filter transmission. This yields a predicted percentage pulse of slightly less than 0.4%, which compares favourably with the values obtained by Groth *et al.*[1] (0.1–0.2%). We note that various power laws suggested by Ulmer *et al.*[5] predict pulsation amplitudes that are far too large, unless a low frequency turnover is assumed.

The success of the flat spectrum hypothesis in predicting the observed pulse height and the absence of strong emission lines in the visual (ref. 2 and G. Gilbert, private communication) render the often discussed hidden soft X-ray heating source (ref. 6, for example) unnecessary.

We thank S. Carswell, P. A. Strittmatter, R. I. Thompson, F. J. Vrba, and J. A. J. Whelan for advice and assistance.

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Received July 11, 1973.

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Positronium Origin of 476 keV Galactic Feature

Leventhal[1] has noticed that the γ-ray spectrum due to the annihilation of positronium, which consists of two 511 keV photons from the singlet state and three photons from the triplet state, produces a spectral feature (line) with an apparent peak at an energy less than 511 keV when viewed with a γ-ray telescope having a Gaussian energy resolution. With the energy resolution of the telescope[2] used to detect the 1.8×10^{-3} cm^{-2} s^{-1} galactic feature at 476 ± 24 keV, Leventhal[1] calculates that the observed peak will lie at 490 keV. I calculate, moreover, that if the positronium spectrum sits atop a steeply falling continuum due to other sources, as is observed, then the apparent peak can easily fall near 476 keV where it was observed. Furthermore, the actual data[2] on the observed feature look like a positronium feature, because there are very few (statistically zero) photons (as opposed to pulses) with energies greater than about 511 keV, indicating a sudden drop in the spectrum there. I therefore take Leventhal's suggestion seriously and show here that explosive nucleosynthesis is a plausible source of the positrons.

The primary sources of positrons from explosive nucleosynthesis should be ^{56}Co, the progenitor of ^{56}Fe with a half life of 77 d, and ^{44}Sc, the daughter of 48-yr ^{44}Ti and progenitor of ^{44}Ca. Either or both could be the source of sufficient positrons to account for the observed feature. To see this requires an estimate of the rate of synthesis of the parent nuclei. I shall assume as a model that 1.7×10^9 supernova events during galactic history[3] synthesized the galactic concentrations of ^{56}Fe and ^{44}Ca. Then the average supernova yield is 3.0×10^{54} atoms of ^{56}Co and 5.6×10^{51} atoms of ^{44}Ti. The decay of these nuclei after explosive ejection provides the positrons. Leventhal[1] argued that if the density is less than 10^{-9} g cm^{-3}, the emitted positrons will decay primarily through the formation of positronium. If the details of the dynamics are ignored and one merely assumes m solar masses expanding uniformly at an expansion velocity 10,000 km s^{-1}, the mean density would be

$$\bar{\rho}\approx(m/2.1\ t^3)10^6\ \text{g cm}^{-3} \qquad (1)$$

where t is the expansion time (s). This density is sufficiently rare for the positronium mode to dominate for $t>10^5$ s. The optical depth

$$\bar{\rho}R\approx(m/2.1\ t^2)10^{15}\ \text{g cm}^{-2} \qquad (2)$$

is less than 10 g cm^{-2} for $t>10^7$ s, very nearly the mean lifetime of ^{56}Co. Therefore one can roughly estimate that 1/e of the positrons produced by ^{56}Co decay form a positronium annihilation that escapes the expanding remnant. Because the positron emitting branch of ^{56}Co is 20%, we anticipate (0.20/e) 3.0×10^{54} visible annihilations per supernova.

The rate of annihilation of these 2.2×10^{53} positrons is a question of the astrophysical environment. I shall consider one of the two simplest cases. If the lifetime of the positron against formation of positronium is greater than the average