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A POSSIBLE OPTICAL COUNTERPART TO THE X-RAY PULSAR 1E 2259+586

G. G. FAHLMAN,[1] P. HICKSON,[1] AND H. B. RICHER[1]
Department of Geophysics and Astronomy, University of British Columbia

P. C. GREGORY
Department of Physics, University of British Columbia

AND

J. MIDDLEDITCH
Los Alamos National Laboratory

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ABSTRACT

An optical, intensified CCD observation of the field of the 3.49 s X-ray pulsar 1E 2259+586 is discussed. Two stars with $B = 22.0$ and $B = 21.3$ are found to lie 4''.9 and 6''.3 away from the nominal X-ray position determined by the High Resolution Imager (HRI) camera of the *Einstein Observatory*. The fainter star is identified as the optical counterpart to the pulsar on the basis of recently detected infrared pulsations. No other star with $B \lesssim 23$ is found within an 8'' radius circle around the HRI position. The absence of a bright optical counterpart rules out a massive binary companion for the pulsar. If the pulsar has a binary companion, it must be a low-mass main-sequence dwarf or a degenerate star. The implication of the binary hypothesis is that the neutron star was formed in a Type I supernova explosion which occurred in a preexisting close binary configuration. The possibility that the pulsar is powered by accreting matter from a molecular cloud observed at the western edge of the supernova remnant surrounding the pulsar is briefly discussed.

Subject headings: pulsars — X-rays: sources

I. INTRODUCTION

The X-ray pulsar 1E 2259+586 (Fahlman and Gregory 1981) is located within a supernova remnant (SNR) discovered in the X-ray band with the *Einstein Observatory* (Gregory and Fahlman 1980*a*). The SNR was independently discovered in the radio band by Hughes, Harten, and van den Bergh (1981) and shows up prominently in the 6 cm radio survey of Gregory and Taylor (1981). Spectroscopic observations of optical filaments in the region show the high [S II]/Hα ratio characteristic of SNRs (Blair and Kirshner 1981).

The radio observations give a distance to the remnant of between 3.6 kpc and 4.7 kpc (Gregory and Fahlman 1980*a*; Hughes, Harten, and van den Bergh 1981). An age of $\sim 10^4$ years is derived from the standard blast wave model (see, e.g., Gorenstein and Tucker 1976).

The object is of more than usual interest because (1) it is one of the few examples of a direct association of an X-ray pulsar with a SNR, (2) the SNR may be interacting with a large molecular cloud on its western boundary (Heydari-Malayeri, Kahane, and Lucas 1981), and (3) the X-ray image suggests the existence of a large-scale jet which links the outer rim of the diffuse emission with the pulsar (Gregory and Fahlman 1980*b*).

Here we report a new accurate position for the X-ray pulsar and discuss an image of the field obtained with an intensified CCD at the prime focus of the Canada-France-Hawaii Telescope. Two faint candidates for an optical counterpart are identified. Recent infrared photometry of the field containing the southern candidate shows pulsations in the 0.9–2.4 μm band with a dominant frequency which is smaller, by about 1 mHz, than the previously reported X-ray frequency.

II. OPTICAL OBSERVATIONS

The University of British Columbia CCD system is described in detail by Hickson, Fahlman, and Walker (1981). The detector is a 100×100 element surface channel CCD kindly made available to us by Bell Northern Research of Ottawa, Ontario. By current standards, the device has a low quantum efficiency ($\sim 5\%$), and our experience with it indicated that it would be more efficient to use it behind an image intensifier. The data reported here were obtained with the CCD optically coupled to the phosphor output of a Varo microchannel intensifier with an S-20 photocathode. The observing run was dedicated to another project, and because of time pressure we were able to

[1]Visiting Astronomer, Canada-France-Hawaii Telescope, operated by the Centre National de la Researche Scientifique of France and the University of Hawaii.

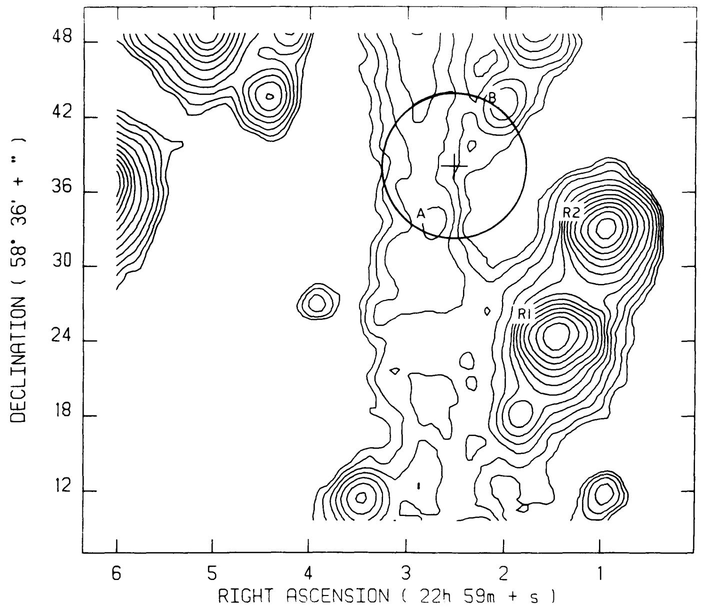

FIG. 1.—Isophotal contours of the blue CCD image are shown. The HRI position of the pulsar is marked by the plus sign which also indicates the $\pm 1''$ astrometric error in locating its absolute position. An error circle of 6″ radius has been drawn around this position. The two candidate stars, A and B, are indicated as are the two 17 mag stars, R1 and R2, used as position reference points. The lowest contour shown has a surface brightness of $\sigma(B) = 25.8$ mag arcsec^{-2} and the contours are spaced at intervals of 0.5 mag.

TABLE 1

POSITIONS[a] AND MAGNITUDES

Star	α (1950) ($00^h00^m00^s.00$)	δ (1950) $00°00'00''.0$	B
R1......	22 59 01.57	58 36 24.0	17.25 ± 0.05
R2......	22 59 01.02	58 36 32.4	17.52 ± 0.05
A.......	22 59 02.81	58 36 33.3	22.0 ± 0.2
B.......	22 59 02.12	58 36 42.4	21.2 ± 0.1

[a] The absolute positions of the reference stars are uncertain by $\pm 1''.2$ based on repeated measurements on the sky survey prints. The relative positions of the stars listed are accurate to $0''.4$.

secure only two images of the pulsar field on the night of 1981 July 6. One 15 minute exposure was obtained without a filter; the other, referred to as the b-frame, was a 15 minute exposure through a Corion interference filter centered at 4500 Å with a FWHM bandpass of 700 Å. The b-frame photometry discussed below has been transformed to Johnson *B*-magnitudes through a calibration based on photometric standards in the globular cluster M4 (see Richer *et al.* 1981). The unfiltered frame reaches about 1 mag deeper than the b-frame, but because of uncertain calibrations for the flat field and sky background, it is not as reliable at the faint limit as the b-frame.

A contour diagram of the b-frame is shown in Figure 1. This picture has been divided by a flat field, has had cosmetic defects repaired, and has had a constant sky background subtracted. The positions of the two bright stars on the western edge of the field were determined using standard astrometric procedures on the corresponding red Palomar Observatory Sky Survey (POSS) print and are given in Table 1.

The position of the X-ray pulsar, obtained from a 20,000 s observations with the High Resolution Imager (HRI) camera of the *Einstein Observatory* (Giacconi *et al.* 1979), is (1950.0):

$$\alpha = 22^h59^m2^s.63, \qquad \delta = 58°36'37''.6.$$

The error in the absolute position is not well determined. The HRI reduction procedure included corrections for the effects of the Earth's magnetic field which should significantly reduce what was previously the dominant source of error (F. D. Seward, private communication). Given the remaining identifiable sources of error, we feel that an acceptable identification should lie within about 6″ of the nominal position. We note that this new position differs by $5''.6$ (almost due west) from our previously reported position obtained from an earlier 2000 s HRI exposure (Fahlman and Gregory 1981) which did not include the corrections for the Earth's magnetic field. The revised position was located on Figure 1 with respect to the intensity centroids of the two reference stars on the blue CCD frame and is indicated by the plus sign.

The two candidate stars are labeled on Figure 1: A is $4''.9$ away from the HRI position and B is $6''.3$ distant. These are the only two visible stars which are sufficiently close to the HRI position to be acceptable as

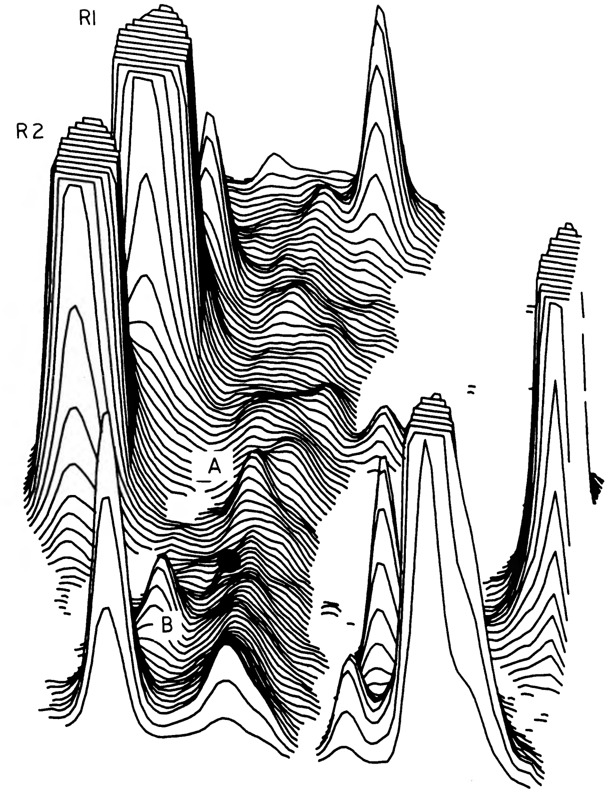

FIG. 2.—This shows a perspective view of the intensity plane depicted in Fig. 1 as seen from the north at an angle of 50° above the plane. The intensity is on a linear scale to show the structure associated with the emission ridge. The HRI position of the pulsar is indicated by the solid circle between the two candidate stars, A and B. These two stars define the diameter of the error circle associated with the HRI position (see Fig. 1). Note that the brighter stars, including R1 and R2, have been artificially clipped; only the bottom 6% of the dynamic range is illustrated. A 3 × 3 boxcar smoothing was applied to the data.

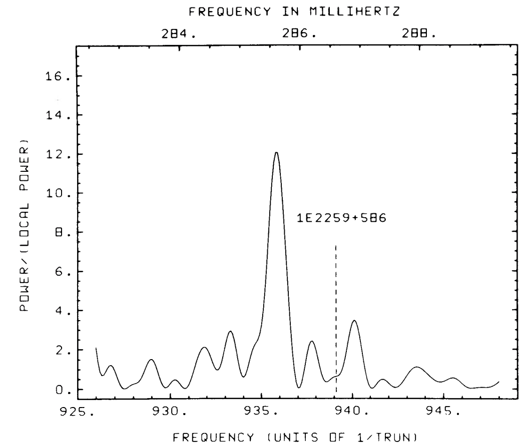

FIG. 3.—The section of the Fourier power spectrum of the infrared data near the X-ray pulsation frequency of 286.6 mHz (indicated by the vertical dashed line) is shown. The infrared peak is downshifted by 1 mHz consistent with the hypothesis that the emission is due to reprocessing of the X-ray pulses in the atmosphere of a companion star. Note that no direct infrared pulses (at the X-ray frequency) are seen. This continuous power spectrum was generated by interpolation using the discrete Fourier amplitudes from a 65536 sample fast Fourier transform.

candidates for the optical counterpart to the pulsar. The next closest star is a very faint object located SE of A about 9″ distant from the HRI position. The coordinate positions of A and B were determined from their offsets from the reference stars and are listed in Table 1 together with estimates of their B-magnitudes.

It is evident that the HRI position is at the edge of a narrow ridge of emission. Our unfiltered CCD frame is slightly offset with respect to the b-frame and shows the ridge in the same relative position, so it is certainly not a CCD artifact. An examination of the red POSS print revealed a faint, elongated smudge which appears to coincide with the emission ridge in the CCD frame. Obviously the presence of the emission ridge greatly complicates the assessment of what limiting magnitude could be placed on a star near the nominal position. This is somewhat more graphically illustrated by Figure 2 which is a perspective view of the image plane. Some numerical experiments in which star images were added to the observed data indicate that a star with $B = 23$ would be fairly easily discerned anywhere on the ridge, whereas a star with $B = 24$ would be very difficult to identify. Consequently we feel that, apart from the two identified stars, any other candidates for the optical counterpart to the pulsar within $\sim 6''$ of its HRI position must have $B > 23$.

It can be seen in Figure 2 that star B sits outside the ridge but its image is contaminated somewhat by the bright star to the NW. The magnitude of star B was estimated by numerically integrating the mean of luminosity profiles taken to the SW and SE. Star A, however, sits right on the ridge. Noting that the ridge runs more or less N-S, we adjusted the luminosity profile through the star in that direction by subtracting a constant to represent the ridge until the profile matched reasonably well a scaled profile for star R1.

As a final point, we note that star B is easily seen on the red POSS print, whereas star A is part of a blotchy distribution at the plate limit. This suggests that star A may be somewhat bluer than B and hence a somewhat more interesting candidate. It is star A which appears to show infrared pulsations.

The infrared photometry was done at the NASA Infrared Telescope Facility on Mauna Kea on 1981 December 19. A 5″.7 aperture was used which, if well centered on star A, would exclude all other stellar objects visible in Figures 1 and 2. The data were obtained through a broad-band filter (0.9–2.4 μm) for 3276.8 s. The relevant portion of the power spectrum of these data, interpolated as in Middleditch *et al.* (1981), is shown in Figure 3. The dominant frequency is at 285.6 mHz, whereas the X-ray frequency (Fahlman and Gregory 1981) is 286.6 mHz. There is no evidence for infrared pulses at the X-ray frequency. A detailed analysis of the infrared data will be presented elsewhere (Middleditch, Pennypacker, and Burns 1982). Here we note only that the frequency shift can be understood if the infrared pulsations result from reprocessed X-radiation from an orbiting companion to 1E 2259+586. In any event, the infrared and X-ray frequencies are close enough that the identification of star A as the optical counterpart to the pulsar is reasonably secure.

III. DISCUSSION

The X-ray luminosity of the pulsar has been estimated from a series of fits to the pulse-height analyser (PHA) output of the *Einstein* Imaging Proportional Counter (IPC) camera. Apart from the uncertainty in the calibration of the PHA spectra, there is an ambiguity in interpreting the results of the fitting procedure because of the spectral response function of the device. Essentially, the fits provide a relationship between the spectral temperature (or power-law index) and the surface density of the absorption column to the source. For an exponential spectrum including the Gaunt factor, our results indicate that the pulsar is considerably harder ($kT \gtrsim 1.0$ keV) than the surrounding diffuse emission ($kT = 0.4 \pm 0.1$ keV) and that the column density is higher toward the pulsar ($N_{\rm H} \approx 0.8 \times 10^{22}$ cm^{-2}) than it is toward the diffuse emission as a whole ($N_{\rm H} \approx 0.6 \times 10^{22}$ cm^{-2}). This may be the result of some overlap with the molecular cloud to the west. Based on our distance estimate of 3.6 kpc, the luminosity of the pulsar in the 0.5–4.0 keV band is 2×10^{35} ergs s^{-1} with an uncertainty of perhaps a factor of 2. By analogy with other X-ray pulsars, we expect the X-ray spectrum to extend out to ~ 20 keV so that the total X-ray luminosity may well be a factor of ~ 5 greater than our estimate based on the IPC data. The cataclysmic variables, which are powered by accretion onto a white dwarf, have X-ray luminosities of $\lesssim 10^{32}$ ergs s^{-1} (Becker 1981; Cordova, Mason, and Nelson 1981). The much higher X-ray luminosity of 1E 2259+586 suggests that it is powered by accretion onto a rotating neutron star.

The CCD data presented here show that the optical counterpart has $B \gtrsim 22.0$. In order to specify the ratio of X-ray (L_x) to optical (L_B) luminosity, the optical extinction must be estimated. We adopt a value of $A_B = 5.0$ mag as a reasonable estimate based on the range of column densities found for the X-ray fit and converting these to optical extinction values (Ryter, Cesarsky, and Audouze 1975; Gorenstein 1975). The value is also consistent with the reddening of the central stars of the H II regions S-152 and S-153 (Crampton, Georgelin, and Georgelin 1978) which are likely associated with the nearby molecular cloud. Consequently we find that $L_x/L_B \gtrsim 100$. This large value certainly excludes a massive main-sequence companion to the neutron star.

Among the 25 low-mass X-ray binaries discussed by van Paradijs (1981), the only pulsar is 4U 1626−67. A detailed analysis of the optical pulsations from this system gives an orbital period close to 2500 s and a companion mass of $M_c \lesssim 0.5\ M_\odot$ (Middleditch *et al.* 1981). An approximate analytic theory for systems like 4U 1626−67 has been developed by Li *et al.* (1980). It is based on the assumption that the companion fills its Roche lobe and moves in a circular orbit. Applying it to 1E 2259+586, we find that the observed X-ray luminosity ($L_x \approx 2 \times 10^{35}$ ergs^{-1}) is below the minimum predicted for a main-sequence companion unless the neutron star primary has a rather low mass ($M_x \lesssim 0.5\ M_\odot$). If we adopt $M_x = 1.4\ M_\odot$ and $L_x \lesssim 10^{36}$ ergs s^{-1}, then the theory predicts that a main-sequence companion must have $M_c \gtrsim 0.3\ M_\odot$. With these same constraints, a hydrogen deficient ($X = 0.1$), degenerate companion must have a very low mass ($M_c \lesssim 0.02\ M_\odot$). Apart from the uncertainty in assigning parameter values, the applicability of the theory is questionable because, as mentioned below, the orbit of a companion to 1E 2259+586 is unlikely to be circular.

The pulsed infrared emission corresponds to a magnitude of $H \approx 17.5$. Our adopted extinction in the blue together with the van de Hulst reddening law (Johnson 1966) lead to an estimate of $A_H \approx 0.5$ mag for the infrared extinction. The dereddened H-magnitude of 17.0 for the pulsed emission corresponds to the normal photospheric emission from a K0–K4 dwarf at a distance of 3.6 kpc (Frogel *et al.* 1978). Thus, if the companion is indeed a K4 dwarf, the ratio of pulsed to normal emission at H is 1:1 at least. The mass of a K4 star is about 0.7 $M_\odot$ (Harris, Strand, and Worley 1963) which is perhaps on the high side of what might be expected on the basis of the X-ray luminosity. For cooler, less massive companions, the ratio of pulsed to normal emission would be higher, reaching 10:1 at about 0.3 $M_\odot$. It is evident that, if the companion is producing the infrared pulses, by reprocessing X-rays, its atmosphere will be strongly perturbed. We note that the observed B-magnitude of the optical counterpart is far too bright to be normal photospheric light from a low-mass companion. On the other hand, it is considerably fainter than the other low-mass X-ray binaries (van Paradijs 1981) which suggests that the system does not have a large accretion disk. If the blue light is predominantly from the heated face of the companion, photometric variations are expected on the orbital time scale.

The hypothesis that the pulsar is in a low-mass close binary system is of additional interest because it is the remnant of a fairly recent ($\sim 10^4$ yr) supernova explosion. In view of the long time scales, $\sim 10^8$ yr (Li *et al.* 1980), characterizing the dynamical evolution of the low-mass binary system, it must have existed as a closed binary prior to the supernova explosion and, therefore, the neutron star progenitor could not have been a massive star. The explosion was probably the result of accretion onto a low-mass helium star (Arnett 1979) or onto a white dwarf (Canal, Isern, and Labay 1980), although we note that Chevalier (1981) has argued that exploding white dwarfs would be completely disrupted. In either case the optical filaments in the field of the remnant could be observed for evidence of the expected high Fe abundance believed to be characteristic of Type I supernovae. A second implication of the close binary hypothesis is that the present orbit should be eccentric because of the mass loss associated with the supernova explosion. Since it is unlikely that any appreciable circularization could have occurred in the short time available since the explosion, the observed eccentricity would provide a good estimate of the mass loss associated with the Type I explosion.

An alternative hypothesis to the close binary model is accretion from the adjacent molecular cloud. Spherical accretion onto a compact X-ray source has been discussed in considerable detail by Cowie, Ostriker, and Stark (1978). The characteristics of 1E 2259+586 suggest that of their numerical examples, cases C or D, representing high-efficiency accretion with modest luminosity, are perhaps the most applicable. The principal difficulty in accepting this hypothesis is to understand how the dense material in the cloud can gain access to the pulsar. The X-ray images show that the pulsar is apparently completely surrounded by diffuse X-ray emission. This is not unexpected since the neutron star ought to be safely shielded behind the supernova blast wave which, after only $\sim 10^4$ yr, should still be snowplowing into the molecular cloud (see, e.g., Shull 1980; Wheeler, Mazurek, and Sivaramakrishnan 1980).

There are, however, two caveats to the above: (1) the calculations referred to (and others referenced therein) all pertain to a spherically symmetric case where a supernova explodes within a dense molecular cloud and do not address the asymmetric situation of interest here, and (2) the molecular line observations of Heydari-Malayeri, Kahane, and Lucas (1981) and Israel (1980) together with our radio continuum results suggest the possibility that the cloud may be penetrating the supernova cavity, particularly to the north of the pulsar.

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Note added in proof.—J. Middleditch, C. Pennypacker, and S. Burns again observed star A in the 0.9–2.4 μm passband through a 9″.5 aperture at the IRTF on 1982 July 13. No pulsations were detected down to a limiting magnitude of $H \approx 19$ in a 3 hr run.

G. G. Fahlman, P. H. Hickson, and H. B. Richer: Department of Geophysics and Astronomy, University of British Columbia, 2219 Main Mall, Vancouver, B.C. V6T 1W5, Canada

P. C. Gregory: Department of Physics, University of British Columbia, 6224 Agriculture Road, Hennings No. 325, Vancouver, B.C. V6T 2A6, Canada

J. Middleditch: MS 436, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545