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# OBSERVATIONS OF THE GEMINGA OPTICAL CANDIDATE

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## ABSTRACT

Spectroscopy and photometry is reported of the proposed optical counterpart of the X-ray source IE 0630+178, which in turn is a candidate for identification with the $\gamma$-ray source "Geminga." The magnitudes and colors are $V = 21.2 \pm 0.2$, $B-V = 0.7 \pm 0.3$, $V-R = 0.8 \pm 0.2$. The spectrum is featureless at the present signal-to-noise ratio and defies immediate classification, although the properties of a G star would be consistent with the optical data. If the association with the X-ray source is real, however, the small distance implied by the lack of X-ray absorption would rule out a main-sequence star.

The properties of the X-ray and optical objects and the statistical circumstances surrounding the identification process do not support a compelling argument for the association of the optical, X-ray, and $\gamma$-ray sources. We conclude that the search for Geminga is not over. Nevertheless, the X-ray source seems to be unique, and on this basis, a plausible case can be made that the X-rays are thermal emission from the surface of a neutron star whose optical counterpart is an undetected blue star of magnitude $B \sim 26$. An analogy with the Vela pulsar would incorporate the $\gamma$-ray source and suggest an even more severe difference between the patterns of the $\gamma$-ray and radio beams.

*Subject headings:* gamma rays: general — X-rays: sources

## I. INTRODUCTION

The X-ray source IE 0630+178 was discovered by Bignami, Caraveo, and Lamb (1983, hereafter BCL) in a search of the error box of the high-energy $\gamma$-ray source 2CG 195+04 ("Geminga," Swanenburg *et al.* 1981). BCL concluded, on the basis of the unusual properties of the X-ray source and the low probability of chance coincidence, that the identification of the X-ray source with the $\gamma$-ray source was very likely to be correct. Subsequently, Caraveo *et al.* (1984) found a relatively blue star of $m_v \sim 21.2$ at the edge of the X-ray error box and proposed this as the optical identification of Geminga. Several questions remain as to the significance of the association between the optical, X-ray, and $\gamma$-ray sources, as well as the nature of the optical object. In order to address these questions, we have carried out spectroscopy and further photometry of the Caraveo *et al.* optical candidate. Preliminary results of this work were reported by Halpern and Grindlay (1983) and Halpern *et al.* (1984).

The observations reported in this paper are exclusively of the optical candidate for the *Einstein* X-ray source. Nevertheless, we still regard the reality of the association between the X-ray and $\gamma$-ray sources to be debatable. For example, the 59 s period claimed by Bignami, Caraveo, and Paul (1984) is now being disputed by Buccheri *et al.* (1984). There is one additional point which we feel deserves emphasis. The probability of chance occurrence of an X-ray source as bright as 0.1 IPC count $s^{-1}$ in one IPC field can now be estimated from the number flux relationship of X-ray sources in the galactic plane (Hertz and Grindlay 1984), and is $\sim 5\%$. This result alone would be marginally significant. However, one must take into account the fact that a number of $\gamma$-ray source error boxes were searched in a large *Einstein* program using at least 50 IPC fields (Bignami and Hermsen 1983). Since no other candidate $\gamma$-ray source counterparts were found, the significance of the result is reduced by the total area searched, i.e., the probability of chance coincidence is of order unity. From the opposite point of view, it may be argued that since Geminga is the brightest of the unidentified sources, it may be the only one for which a significantly outstanding X-ray counterpart could be found. In any case, since the statistical significance is weak, the correctness of the X-ray identification must be established by some unusual property of the X-ray source, a point which was recognized by BCL.

## II. ASTROMETRY

In order to obtain an accurate position for the optical candidate, a CCD image at the prime focus of the Palomar 200 inch (5 m) telescope was taken by J. Kristian and J. Mould on the night of 1983 November 3. The position was derived with respect to the grid of SAO stars on the Palomar Observatory Sky Survey (POSS) plate by transforming the CCD pixel coordinates of a set of eight secondary standards to $\alpha(1950)$, $\delta(1950)$. The resulting position is $\alpha = 6^h30^m59^s.37$, $\delta = +17°48'30''.2$ with uncertainties of $\pm 0''.5$ in either coordinate.

The optical position therefore differs by $4''.2$ from the best fit X-ray position in the *Einstein* high resolution imager (HRI) as given by BCL. Since the error radius of 90% confidence in the HRI is $3''.2$ (Grindlay *et al.* 1984), one may reasonably doubt the proposed optical identification of the X-ray source. Systematic errors in the *Einstein* aspect system and star trackers occasionally cause larger position uncertainties, although no

TABLE 1

PHOTOMETRY IN THE FIELD OF GEMINGA

| No. | $v$ | $g$ | $r$ | No. | $v$ | $g$ | $r$ |
|---|---|---|---|---|---|---|---|
| 1....... | 21.63 | 20.67 | 19.63 | 32....... | 21.46 | 21.10 | 20.70 |
| 2....... | 21.08 | 20.12 | 19.35 | 33....... | 20.12 | 19.37 | 18.44 |
| 3....... | 19.27 | 18.99 | 18.45 | 34....... | >21.55 | >21.82 | 20.48 |
| 4....... | 19.67 | 19.43 | 18.96 | 35....... | >21.55 | 21.62 | 20.39 |
| 5....... | 19.62 | 18.88 | 18.30 | 36....... | >21.55 | 20.94 | 20.40 |
| 6....... | >21.55 | >21.82 | 21.13 | 37....... | 20.79 | 19.89 | 19.23 |
| 7....... | 21.61 | 20.71 | 19.54 | 38....... | >21.55 | >21.82 | 19.53 |
| 8....... | 19.59 | 19.04 | 18.43 | 39....... | >21.55 | 20.94 | 20.26 |
| 9....... | 20.97 | 20.14 | 19.64 | 40....... | 19.43 | 18.51 | 17.83 |
| 10....... | 20.32 | 19.89 | 19.35 | 41....... | 21.61 | 20.70 | 20.30 |
| 11....... | >21.55 | >21.82 | 20.69 | 42....... | 21.01 | 19.75 | 18.84 |
| 12....... | 19.49 | 18.90 | 18.54 | 43....... | >21.55 | 21.90 | 20.02 |
| 13....... | 21.65 | 21.53 | 20.73 | 44....... | >21.55 | 21.51 | 19.93 |
| 14....... | >21.55 | 21.71 | 20.71 | 45....... | 21.75 | >21.82 | 20.27 |
| 15....... | >21.55 | 21.78 | 21.13 | 46....... | 21.23 | 20.73 | 19.68 |
| 16....... | 21.74 | 20.92 | 20.38 | 47....... | 20.14 | 19.76 | 18.95 |
| 17....... | 20.53 | 20.13 | 19.33 | 48....... | 19.93 | 19.39 | 18.74 |
| 18....... | >21.55 | >21.82 | 20.75 | 49....... | >21.55 | 19.94 | 19.13 |
| 19....... | 21.77 | 21.45 | 20.21 | 50....... | 20.75 | 19.75 | 19.17 |
| 20....... | 21.27 | 20.68 | 19.45 | 51....... | 20.97 | 19.73 | 18.91 |
| 21....... | >21.55 | 21.74 | 21.02 | 52....... | 21.56 | 20.50 | 19.89 |
| 22....... | >21.55 | 21.38 | 20.56 | 53....... | 20.29 | 19.46 | 18.95 |
| 23....... | >21.55 | 21.52 | 19.98 | 54....... | 21.75 | 20.58 | 19.88 |
| 24....... | >21.55 | 21.81 | 20.93 | 55....... | 21.75 | >21.82 | 20.12 |
| 25....... | 21.81 | >21.82 | 20.51 | 56....... | 20.93 | 20.01 | 19.38 |
| 26....... | 19.12 | 18.51 | 17.92 | 57....... | 19.51 | 18.90 | 18.11 |
| 27....... | 20.83 | 19.73 | 19.24 | 58....... | 20.26 | 19.30 | 18.44 |
| 28....... | 19.81 | 19.11 | 18.57 | 59....... | 20.04 | 19.50 | 18.37 |
| 29....... | >21.55 | 22.07 | 21.01 | 60....... | >21.55 | 21.22 | 20.36 |
| 30....... | >21.55 | 21.41 | 20.87 | 61....... | 21.62 | 20.83 | 19.86 |
| 31....... | 21.71 | 20.86 | 20.19 | | | | |

such systematic effects (e.g., errors in separation of guide stars) were evident in this HRI observation. The density of stars in the field is quite high. There are 92 stars in a 3′ × 3′ field with $v$ magnitude less than or equal to 21. The probability that a star this bright will fall randomly within 4.″2 of the X-ray position is 16%, i.e., not negligible. Therefore, the optical identification of the X-ray source must rely on some unusual optical property. In this regard, there is a claim (Bloemen 1984) that a faint spot near the plate limit of the red POSS plate of 1955 indicates a proper motion of the optical object of 0.″37 per year. However, in the absence of any confirming historical plates, we regard this as unproven. Ongoing CCD monitoring will shortly be able to confirm or rule out such a proper motion.

## III. PHOTOMETRY

Photometry in the field of IE 0630+178 was done on the night of 1983 November 7 using the SIT Vidicon area photometer (Kent 1979) on the Palomar 60 inch (1.5 m) telescope. The *vgr* (violet, green, red) filter system and standard stars of Thuan and Gunn (1976) were employed. The photometric quality was estimated from the internal dispersion in the 13 standard star measurements to be 0.03, 0.03, and 0.04 mag in $r$, $g-r$, and $v-g$, respectively. In the Geminga field, two exposures in each of the $r$ and $g$ bands, and three in $v$ were taken, with total exposure times of 1600, 1800, and 3900 seconds, respectively. Magnitudes for all unsaturated images in the 3′ × 3′ field were measured and are listed in Table 1. A finding chart for this field, consisting of the summed $r$ band SIT exposures, is shown in Figure 1.

Object No. 32 is the Geminga optical candidate. Limiting magnitudes for a 3 $\sigma$ detection in the $r$, $g$, and $v$ bands are estimated to be 21.07, 21.82, and 21.55, respectively. The Geminga optical candidate has $r = 20.70 \pm 0.16$, $g = 21.10 \pm 0.18$, and $v = 21.46 \pm 0.25$. It is therefore well detected in $r$ and $g$, but the $v$ magnitude is near the detection limit and must be uncertain by at least 0.3 magnitudes. There is an additional source of error in the magnitudes of stars near the edge of the field which is due to pincushion distortion in the SIT detector (Saha 1983). The error can be as high as 25%, but since the effect is independent of wavelength, the colors are unaffected. Color magnitude diagrams for the field are shown in Figure 2. The Geminga candidate is circled. Its $g-r$ color (0.40) is blue in comparison with stars of similar magnitude, although not by a wide margin. The same is true in $v-g$ (0.36), although the weakness of the detection in $v$ makes this color highly uncertain. The $v-r$ color shows the largest deviation, but again, the error in $v$ is likely to be substantial.

The magnitudes were converted to the Johnson *BVR* system in order to make a comparison with the results of Caraveo *et al.* (1984), who present a diagram of $R$ versus $B-R$ derived from CCD photometry of the same field. The conversions from *uvg* to *UBV* are given by Thuan and Gunn (1976). In order to derive $R$ magnitudes, we made use of the data of Wade *et al.* (1979) defining the near-infrared *ri* system. For the 11 stars which are in common with Thuan and Gunn, a least squares fit yields the transformation $(V-R) = 0.484 + 0.736(g-r)$ with a standard deviation of 0.038 mag. The transformed magnitudes for the candidate star are $V = 20.98$, $B-V = 0.69$, $V-R = 0.78$. These results are consistent with those of Caraveo *et al.* (1984), who found $R = 20.4$ and $B-R = 1.2$. The diagram of $R$ versus $B-R$ is shown in Figure 2*d*. The overall distribution of stars is similar to that of Caraveo *et al.*, but with a possible systematic offset of 0.2–0.3 in $B-R$. The separation between the Geminga candidate and the bulk of the field stars is similar in both the diagrams, but it is less precise in ours because of the brighter limiting magnitude in $B$. We conclude that the SIT photometry is consistent with the claim of Caraveo *et al.* (1984) that the candiate star is the bluest for its magnitude, but it does not lend any additional significance to it.

## IV. SPECTROSCOPY

Spectra were obtained on the nights of 1983 September 16 and 17 using the red camera (TI CCD) of the double spectrograph (Oke and Gunn 1982) on the Palomar 200 inch (5 m) telescope. A star of magnitude $r = 20.7$ is not generally visible on the red-sensitive television guider. Therefore, offset coordinates from a nearby (~20″) 17th mag star (kindly supplied by G. Bignami from the CCD images of Caraveo *et al.* 1984) were used to align a long slit at the correct position angle to include both the candidate and the guide star (marked G in Fig. 1). Two exposures were obtained, one of duration 3000 s through a 4″ slit, and one of 4000 s through a 2″ slit. The spectra cover the wavelength range 5000–9000 Å with a resolution of 18 Å. Flux calibration was performed with the standard stars of Oke and Gunn (1983) taken through a 6″ slit.

The narrow-slit spectrum has the better signal-to-noise ratio and is shown in Figure 3. Approximate correction for atmospheric absorption bands longward of 6800 Å was made by fitting smooth functions to the standard star spectra. The resulting spectrum is featureless, with no significant emission or absorption lines. Single pixel features at $\lambda$6240 and $\lambda$6565 are due to imprecise subtraction of night sky features. The spectrum becomes very noisy redward of 8300 Å because of the very bright atmospheric OH emission lines and $H_2O$ absorp-

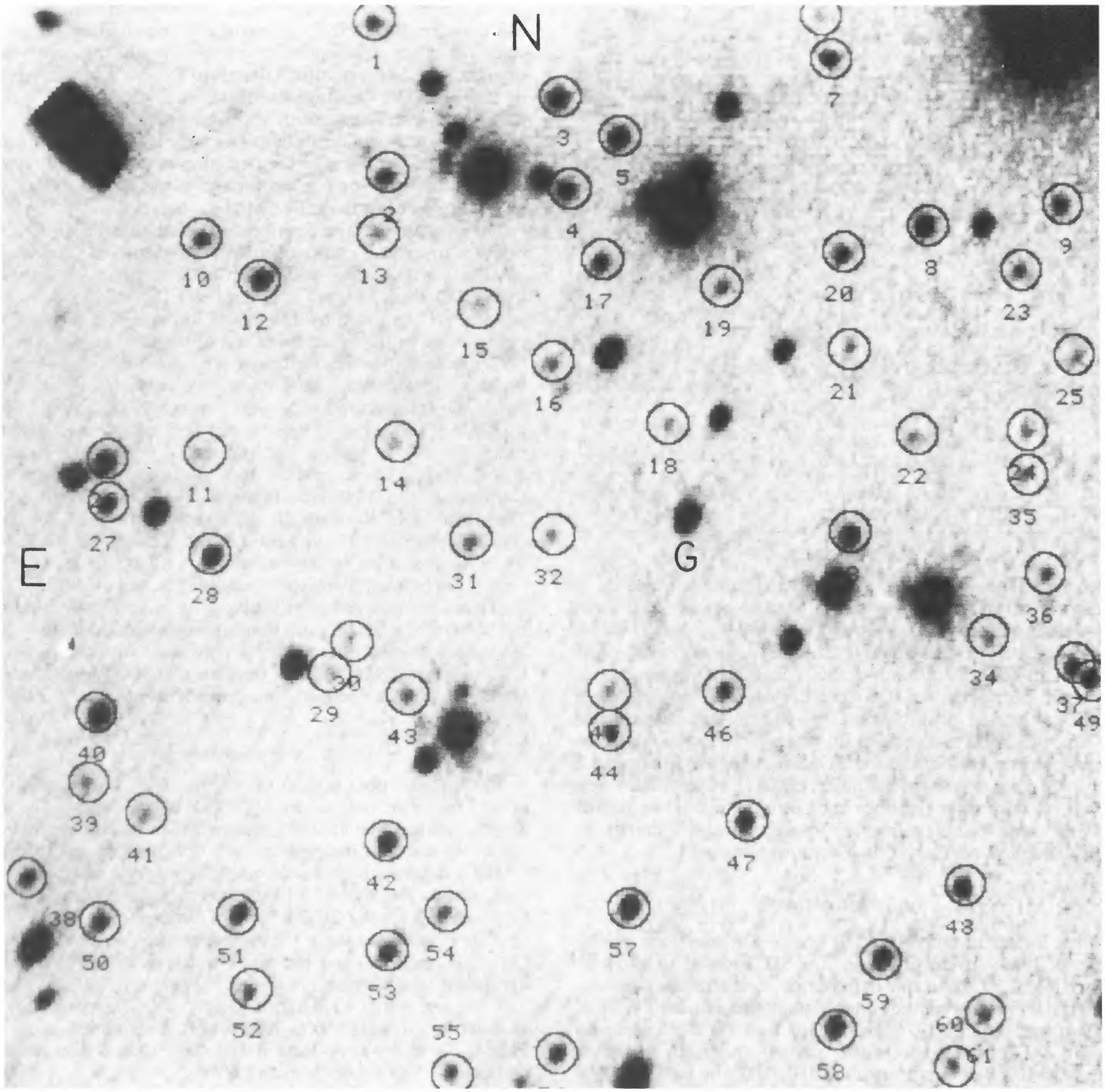


FIG. 1.—A finding chart for the 3′ × 3′ field centered on 1E 0630 + 178. This is a 1600 s *r*-band exposure taken with the SIT Vidicon on the Palomar 60 inch (1.5 m) telescope. Magnitudes of the 61 labeled stars are given in Table 1. The Geminga optical candidate is No. 32. The star labeled G is a guide star which was used to orient the slit. North is up, east is left. The rectangular feature in the upper left corner is a permanent artifact of the SIT tube.

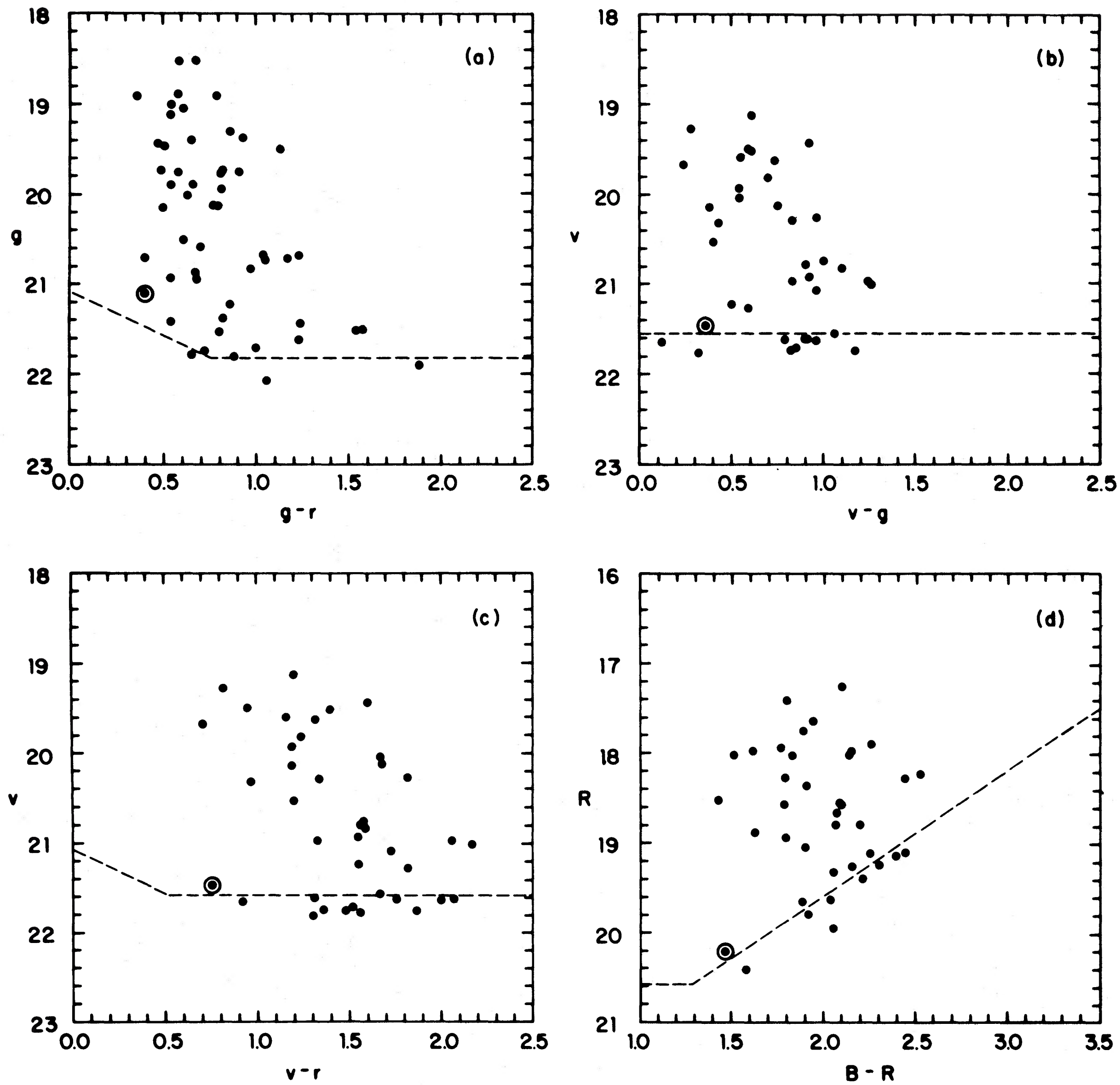


FIG. 2.—Color-magnitude diagrams for stars in a 3′ × 3′ field centered on 1E 0630+178. The data are taken from Table 1. Dashed lines show approximate limiting magnitudes for a 3 $\sigma$ detection. Diagrams (*a*), (*b*), and (*c*) are in the Thuan and Gunn system. Diagram (*d*) shows a conversion to Johnson *BVR* to permit comparison with Caraveo *et al.* The Geminga optical candidate (No. 32 in Table 1) is circled. Errors are approximately 0.3 mag near the detection limit, and 0.1 mag for the brighter stars.

tion. The 4″ slit spectrum (not shown ) was used to estimate that $V = 21.3$ and $V - R = 0.9$ with an error of 0.2 mag in each due to uncertainty in the amount of light lost. These magnitudes are consistent with the results of the SIT photometry.

There still could be stellar absorption lines buried in the noise. Support for this possibility is provided by the spectra of the guide star G and star No. 31 which were obtained in the same exposure due to their fortuitous alignment. The excellent spectrum of star G shows it to be a G type, with measured equivalent widths of lines in the red portion of the spectrum listed in Table 2. The signal-to-noise ratio (SNR) (per pixel) necessary to achieve a statistical significance of $n$ $\sigma$ in the detection of a line having equivalent width $W$ is roughly

$$\mathrm{SNR} = ndN^{1/2}W^{-1} ,$$

where $d$ is the dispersion in Å per pixel and $N$ is the number of pixels containing the line ($\sim 4$). The spectrum of the Geminga candidate has a maximum SNR of 10 between 6500 and 7000 Å per pixel. If it had the same spectrum as star G, the Hα line

TABLE 2

G STAR EQUIVALENT WIDTHS

| Line, $\lambda$ | $W$(Å) |
|---|---|
| Ca + Fe 5268 ....... | 2.5 |
| Na D 5892 .......... | 3.2 |
| Ha 6562 ............ | 2.4 |
| Ca II 8498 ........... | 1.2 |
| Ca II 8542 ........... | 2.4 |
| Ca II 8662 ........... | 2.3 |

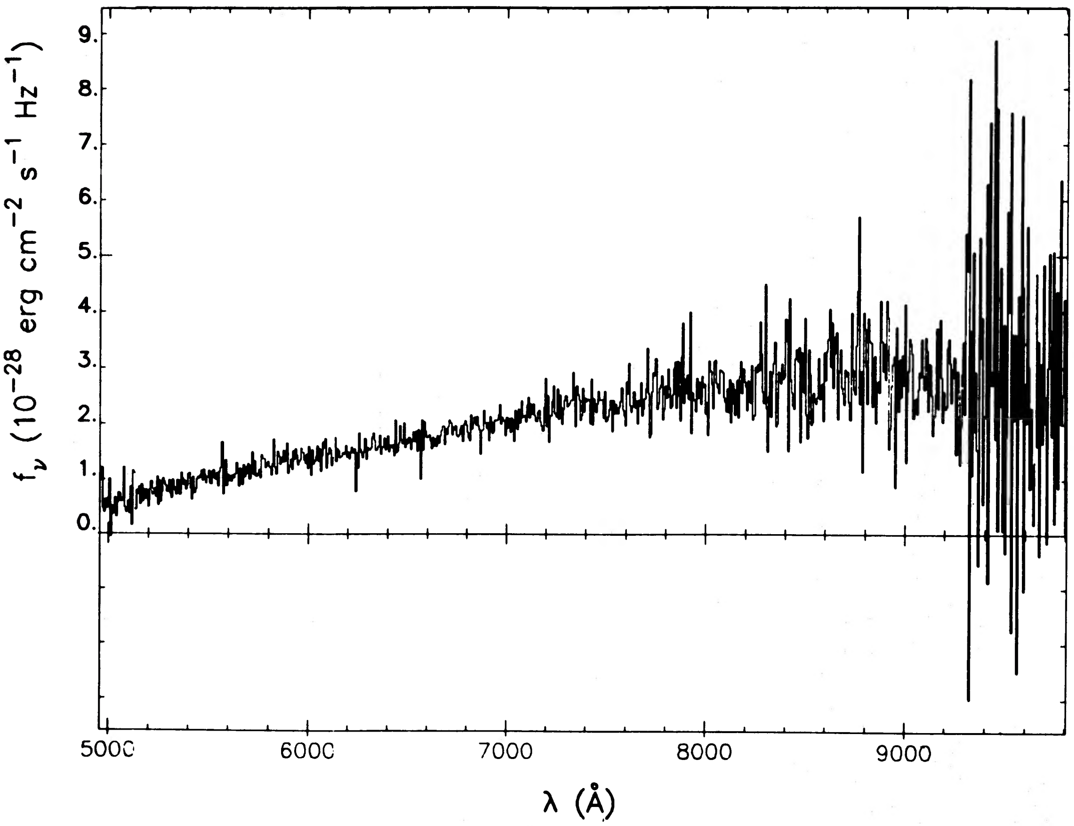


FIG. 3.—Spectrum of object No. 32, the Geminga candidate, taken with the red camera (TI CCD) of the double spectrograph on the Palomar 200 inch (5 m) telescope. Resolution is $\sim 18$ Å. This is a 4000 s exposure taken through a 2″ slit. The poor signal-to-noise ratio at the red end is due to bright atmospheric emission and absorption bands.

($W = 2.4$ Å) would only have a significance of 2 $\sigma$. At least a factor of 2 improvement in signal-to-noise would be necessary to see the line. As a further indication of the nature of the problem, we note that the spectrum of star No. 31 is also featureless, even though the counts are higher than those of the Geminga candidate by $\sim 80\%$. There is, however, a marginal hint of the Mg *b* band at 5175 Å and Ca + Fe at 5268 Å in star No. 31.

The quality of the spectrum is insufficient to allow a firm conclusion to be drawn about the nature of the candidate star. The combination of spectroscopy and photometry, however, can be used to rule out a wide range of normal stellar types. This is done in § V.

## V. INTERPRETATION

The optical identification of the X-ray source must rest on some unusual optical property since the positional coincidence alone is not statistically significant. First we consider the properties of the optical object without regard for information from other wavelengths. The star is relatively blue [Fig. 2 and Caraveo *et al.* (1984)], although we point out that the color is not very blue in an absolute sense since $B-V = 0.7$ corresponds to a late G star. There is a slight blue excess with respect to $V-R$, since the latter color is appropriate for a K3 or K4 star. The interpretation of the colors is complicated by the substantial extinction in this direction. The total neutral hydrogen column density of $4 \times 10^{21}$ (BCL) corresponds to a maximum visual extinction of $A_v \sim 1.9$. When correction for the maximum extinction is applied, the $V-R$ color rules out any star earlier than F0 ($V-R = 0.3$). If we require that the distance be less than 15 kpc (corresponding to height above the galactic plane < 1 kpc), then main-sequence stars earlier than F5 are excluded. The absence of prominent TiO bands in the spectrum around 6200 Å rules out a late K or M star. An F star would probaly show some H$\alpha$ absorption. The only main-sequence star which cannot be excluded on the basis of the spectrum and photometry is a G star. The signal-to-noise ratio is not sufficient to detect the lines which are expected to be the strongest in the red part of the spectrum, namely the Mg *b* band and the Ca II near-infrared triplet. In summary, we cannot make a conclusive argument for exceptional optical properties which would compel us to claim an identification.

The interpretation so far has not made reference to the properties of the X-ray source. In the remainder of this section we shall consider the two alternatives, namely that the optical star is or is not associated with the X-ray source and explore the ramifications.

If we hypothesize for the moment that the optical object is indeed associated with the X-ray source, then an additional constraint comes into play. BCL found that the X-ray spectrum is very soft with a limit on $N_H$ of less than $2 \times 10^{20}$. The equivalent extinction is $A_v \leq 0.1$, and implies that the distance is at most a few hundred parsecs. If the optical candidate is a G dwarf, however, the distance cannot be less than 4.5 kpc. These two distance estimates are contradictory and imply that if the identification is correct, the optical counterpart of 1E 0630+178 cannot be a main-sequence star. An intriguing possibility is that of a DG white dwarf. These stars show Ca II

H and K (we do not yet have a spectrum in the blue), but no hydrogen lines. $B-V$ ranges from 0.5 to 0.7, and $M_v$ is 14–15. The distance would therefore be 150–250 pc, consistent with the lack of X-ray absorption. A DC white dwarf would also be allowed. Alternatively, if the optical radiation is nonthermal, the spectral index $\alpha$ is approximately 1.9 (where $F_\nu \propto \nu^{-\alpha}$) with a normalization of 16 $\mu$Jy at 5500 Å. We can estimate the ratio of X-ray to optical luminosity $L_x$(2–11 keV)/$L_{opt}$(3000–7000 Å) as defined by Bradt and McClintock (1983). $F_{opt}$ is about $6.3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$. The X-ray luminosity is problematic, since the flux of $2.2 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ (BCL) was measured by *Einstein* at lower energies (0.5–4.5 keV). Given the extreme softness of the spectrum, the 0.5–4.5 keV flux is likely to be an overestimate of the corresponding 2–11 keV flux for which the ratio is defined. Therefore the ratio $L_X/L_{opt}$ is best given as an upper limit of 35, but it could easily be several times smaller.

The hypothesized cool white dwarf is unlikely to be the direct source of the X-rays via photospheric emission. All the known photospheric X-ray sources are hot DA white dwarfs (Kahn *et al.* 1984) which are much brighter and bluer in the optical. In addition, a blackbody surface temperature of $0.08 \leq kT \leq 0.10$ keV, as measured by BCL, would require an IPC luminosity of at least $3 \times 10^{36}$ ergs s$^{-1}$ and place the source farther than 100 kpc, a distance which is incompatible with the lack of X-ray absorption, among other things. The alternative of coronal emission is not consistent with any known examples because of the high $L_X/L_{opt}$ ratio and the very soft X-ray spectrum of this source. Assigning the optical object to the role of a binary companion, as was done by Bignami, Caraveo, and Paul (1984), does nothing to explain the source of the X-rays, or the very soft spectrum. There is no prototype for such a system. The absence of optical variability and emission lines is uncharacteristic of cataclysmic variables, for example.

If we now adopt the position that the true optical counterpart of the X-ray source has not yet been found, then it must be something intrinsically fainter than a cool white dwarf. Interestingly, the uniqueness of the X-ray source is still a factor, and there is motivation to argue for identification with Geminga even in the absence of an optical counterpart. A plausible connection is via a neutron star which is similar to the Vela pulsar, as first argued by BCL. In this case, the assumption of blackbody emission from all or part of the surface of a neutron star results in a more reasonable distance limit of less than 500 pc. A point source of X-ray emission coincident with the Vela pulsar has now been found (Harnden, Grant, and Seward 1985) with a flux of $3.1 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, about 14 times brighter than that of Geminga. The spectral fits permit at least half of this flux to be blackbody emission at $10^6$ K. If the temperatures of Vela and Geminga are the same, then the optical counterpart of Geminga may be an as yet undetected blue star (emitting in the Rayleigh-Jeans regime) which is 2–3 magnitudes fainter than the Vela pulsar [$B = 23.7$, Lasker (1976)], or $B \sim 26$. The major difference between the two objects would then be the lack of a radio pulsar for Geminga. A substantial difference between the radio and $\gamma$-ray beam patterns could be invoked to account for this. Indeed, the pulse profiles of Vela are radically different in the radio and $\gamma$-ray (Bignami and Hermsen 1983), indicating that differences in the beam patterns are likely.

## VI. CONCLUSIONS

We cannot convincingly demonstrate that the candidate star is the correct identification of the X-ray source 1E 0630+178. Firm proof awaits the determination of the nature of the optical object, for which the present spectrum is not quite adequate. It is still possible that the star is a distant G dwarf and unrelated to the X-ray source. If the star is required to be nearby, consistent with the lack of X-ray absorption, then it could be a DG or DC white dwarf. Statistical as well as physical arguments make it very likely that the true optical counterpart has not yet been detected. An important aspect of this investigation is the apparently unique nature of the X-ray source *whether or not the optical identification is correct*. The only interpretation which is consistent with an established prototype would have Geminga be a neutron star with optical, X-ray, and $\gamma$-ray properties very similar to those of the Vela pulsar.

The present spectrum was obtained during the least favorable part of the observing season. It is possible to obtain a spectrum with considerably better signal-to-noise ratio using the same instrument and integrating for a substantial fraction of the night. Such an observation would be able to detect the spectral features needed to confirm or rule out the G star hypothesis. A spectrum in the blue region around Ca II H and K would be very useful, albeit more difficult to obtain. Further photometry over a broader wavelength range, especially including the blue and ultraviolet, could establish the uniqueness of the star based on the continuum energy distribution. Finally, any detection of variability, such as the 59 s period claimed for the X-rays and $\gamma$-rays (Bignami, Caraveo, and Paul 1984), would secure the identification with Geminga.

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