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OPTICAL STUDY OF THE GEMINGA CANDIDATE FIELD[a)]

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ABSTRACT

We have observed the field of the x-ray source 1E 0630 + 178, proposed as a probable counterpart of the γ-ray source 2CG 195 + 04 (Geminga). Deep CCD images of the field show two very faint optical sources within the x-ray error circle, as well as the 21 mag star (hereafter referred to as the G candidate) proposed earlier as the possible optical counterpart. The G candidate does not have a proper motion greater than 0.15 arcsec yr^{-1}. The spectrum of this object shows no strong emission or absorption features. We conclude that the G candidate is most probably a distant G dwarf or a nearby, cool, white dwarf. We believe that one of the fainter objects within the x-ray circle is more likely to be the true counterpart of the x-ray source, and possibly of the γ-ray source as well. This result is consistent with the interpretation of Geminga as a nearby neutron star, if all the γ rays are generated by some nonthermal mechanism. Deep Hα images do not reveal presence of any emission-line nebulosity (e.g., a supernova remnant).

The mystery of Geminga, the second-brightest source in the *COS-B* γ-ray catalog (Swanenburg *et al.* 1981), lured many observers into a tedious chase, and caused appearance of almost as many theoretical papers as there were γ photons collected. The *COS-B* γ-ray error circle ($\sim 0^\circ.4$ radius) contains far too many optical sources (none obviously interesting) for it to be useful. One plausible approach is to look in the "next" wavelength range, viz., the x-ray region. This was done by Bignami, Caraveo, and Lamb (1983; hereafter referred to as BCL83), who found four x-ray point sources in the Geminga field, and proposed one in particular, 1E 0630 + 178, as the most promising candidate for the counterpart of Geminga. Subsequently, a 21 mag star was found just outside the *HEAO-B* satellite HRI 90% confidence x-ray error circle, and proposed as the possible optical counterpart (Caraveo *et al.* 1984). This star, often referred to as the G candidate, was investigated by several groups (Caraveo *et al.* 1984; Halpern, Grindlay, and Tytler 1985, hereafter referred to as HGT85; Sol *et al.* 1985; Kulkarni and Djorgovski 1985, 1986).

We have obtained CCD (charge-coupled device) images of this field and CCD spectra of the G-candidate star on several occasions, as described in the companion paper (Kulkarni and Djorgovski 1986, hereafter referred to as KD86). The images obtained on the night of 24 February 1985 UT had the best seeing (FWHM$\simeq$1.5 arcsec). We use a digital stack of those images, ten in the r_S band (Djorgovski 1985), with a total effective exposure of 2408 s, plus two images obtained on the night of 25 February 1985, in a 100 Å-wide band centered on the Hα line wavelength, and having equally good seeing, with the total exposure of 2400 s. In order to minimize the loss of spatial resolution, images were interpolated to twice the sampling (to the pixel size of 0.365 arcsec) before registration and stacking. A zoom-in on the region of 1E 0630 + 178 is shown in Fig. 1(a). Intensity cuts through the objects of interest are shown in Fig. 1(b).

We derive the equatorial coordinates for the G candidate (epoch 1950.0): $\alpha = 06^\mathrm{h}30^\mathrm{m}59^\mathrm{s}.381$, $\delta = +17^\circ 48' 30''.84$ with estimated errors of 0.4 arcsec in each coordinate. Our position, based on the system defined by 25 nearby SAO stars (KD86), differs from the position derived by HGT85 by 0.66 arcsec, and from the position derived by Sol *et al.* (1985) by 1.04 arcsec. HGT85 quote errors of 0.5 arcsec, whereas Sol *et al.* quote errors of 0.3 arcsec in each coordinate. Thus, the discrepancies can be explained by the measuring errors. We will use hereafter our position of the G candidate. This object is then just outside the 90% confidence error circle of 1E 0630 + 178, which has a radius of 3.3 arcsec (quadratic sum of the 3.2 arcsec radius quoted by HGT85, and our 0.4 arcsec positional error). The discrepancy of positions is thus marginally significant.

We used our images to place constraints on the proper motion of the G candidate. Although our time baseline is short (only 90 days), we could produce a reasonably good measurement, because only relative astrometry is needed, and all the data were obtained with the same instrument, and processed in an identical way. For this purpose we used the stars A through H (KD86) to define a relative astrometry reference frame. Relative positions were computed for the G candidate and the faint comparison stars 1, 2, 4, and 7 as a control. For each night, a stack frame of all exposures was produced, and pixel positions of stars were measured. We used the mirror-autocorrelation digital centering method (Djorgovski and King 1984). The centering errors were typically of the order of 0.01 arcsec in each coordinate for all stars used. We then transformed all coordinates to the system of 24 February 1985, by allowing for shift, rotation, and stretch of coordinate systems for individual nights. This transformation does not introduce any additional errors, and compensates well for the slight differences that are present between the coordinate systems for different nights. From the coordinate residuals for the reference stars A–H, we estimate the stability of our relative astrometry baseline to be of the order of 0.01 arcsec in each coordinate. For each night, we compute the weighted mean centroid of stars A–H, and subtract it from the positions of the G candidate and the comparison stars. Finally, we subtract the mean relative position for each star. The results are shown in Fig. 2. A data-quality-weighted least-squares fit for our data only gives a *formal* solution for the proper motion of the G candidate of $\mu_\alpha^{\mathrm{app.}} = +0.380$ arcsec/yr, and $\mu_\delta^{\mathrm{app.}} = -0.046$ arcsec/yr. Dr. Jules Halpern kindly communicated to us the position measurements of the G candidate and a number of stars in

[a)] Based in part on research done at Lick Observatory, University of California.

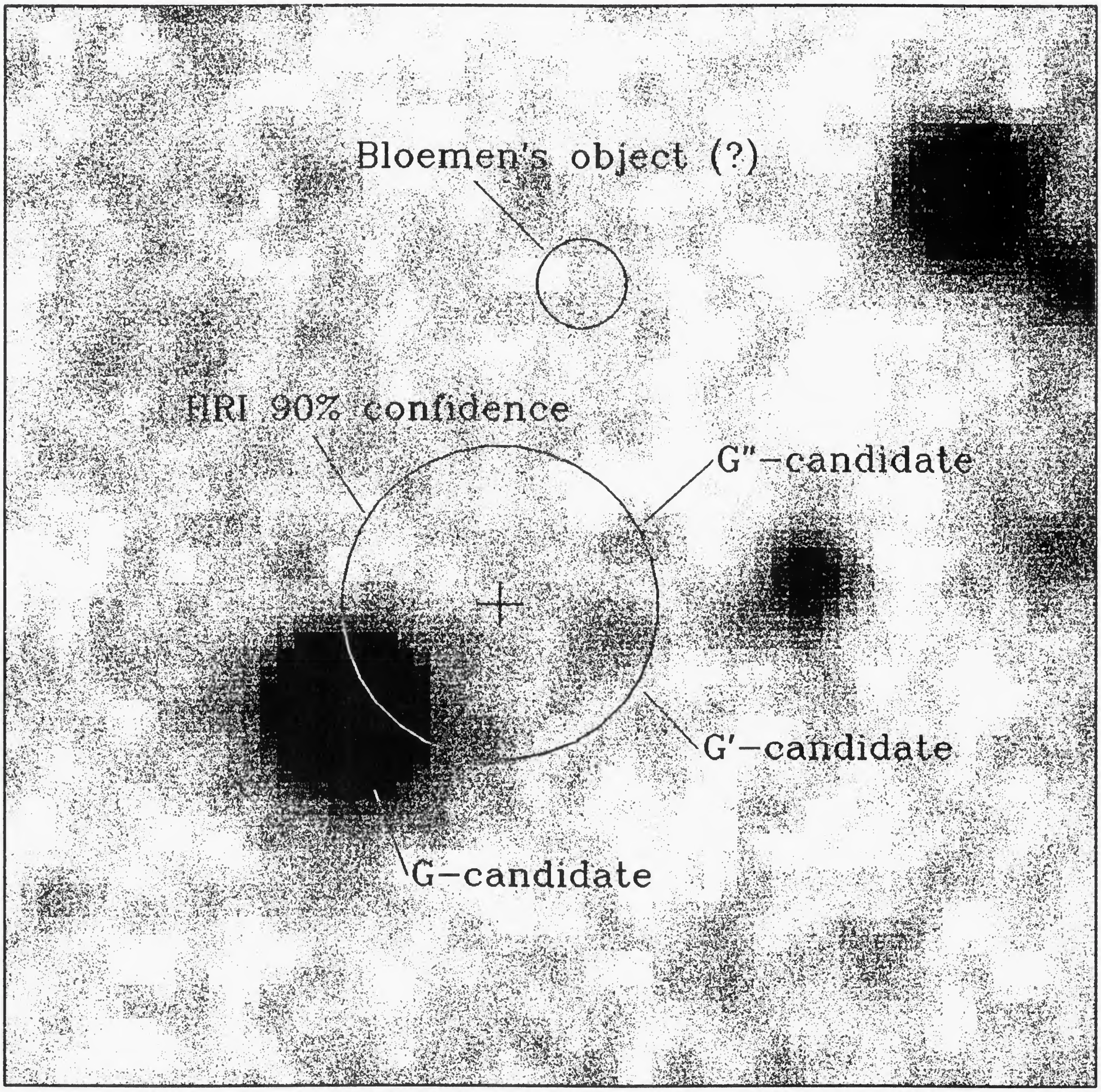

FIG. 1. (a) CCD image of the 1E 0630 + 178 field. North is up, east to the left; the field is a square of 23.4 arcsec on a side. The position centroid of 1E 0630 + 178 is marked with a cross, and the 90% confidence error circle around it includes our astrometric errors of 0.4 arcsec in each coordinate (KD86). Optical candidates for the x-ray (and possibly the γ-ray) source are indicated. The limiting red magnitude for this image is about 25.5.

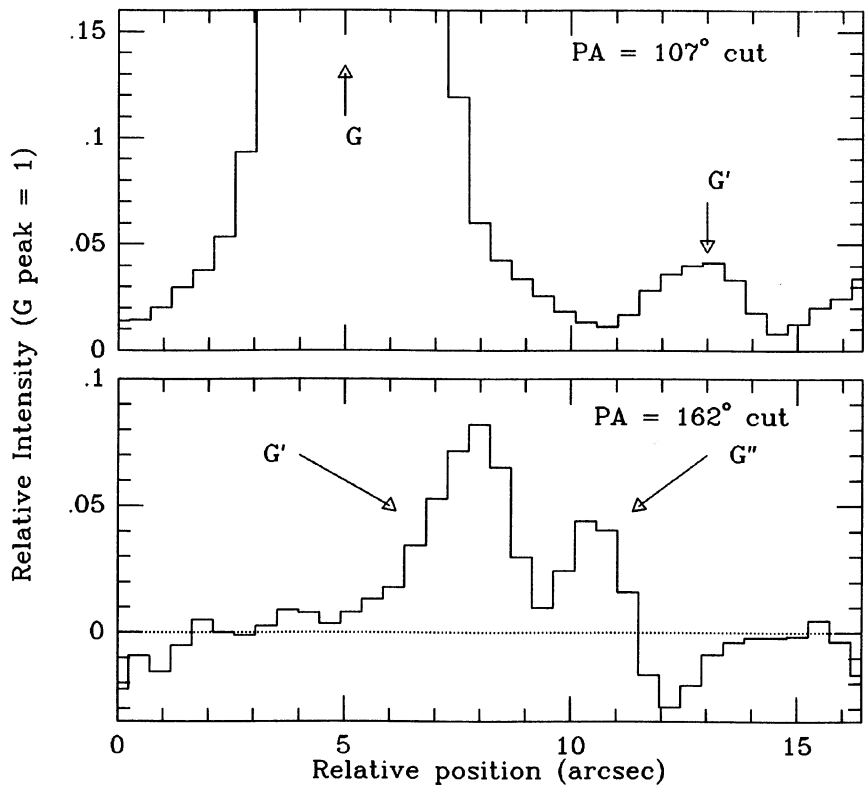

FIG. 1(b). Sky-subtracted intensity cuts through the objects of interest, in the image shown in Fig. 1(a). The cuts represent averaged intensity in strips 1.46 arcsec wide, with position angles as indicated. The intensity was renormalized so that the peak value of the G candidate is 1.

this field, from the CCD data obtained on the night of 3 November 1983 UT at Mount Palomar (HGT85). We transformed their coordinate system into ours, and re-evaluated the proper motion using this longer baseline (~ 1.32 yr). The formal least-squares fit yields $\mu_\alpha^{\rm app.} = +0.138$ arcsec/yr, and $\mu_\delta^{\rm app.} = -0.043$ arcsec/yr. We consider the latter result to be more reliable, since it is based on the longer time baseline. Note that the $\mu_\alpha^{\rm app.}$ solution decreased by a factor of 3, when a longer time baseline was used. This is indicative of the presence of systematic errors in this measurement. Such systematics probably do exist; the distortion constants of the Shane telescope Cassegrain CCD camera are not known, and we cannot compensate for them. As can be seen from Fig. 2, the comparison stars show "proper motion" at least equal to the G candidate, and thus we can only say that the *upper limit* for the total proper motion of the G candidate is about 0.15 arcsec/yr. At least, we can conclude that a high proper motion suggested for the G candidate (Bloemen 1984) seems to be excluded. Note that the sign of the measured proper motion is the opposite from the expected paralactic motion. Similar constraints to the proper motion of this object were also obtained by other groups (Sol *et al.* 1985; Lecacheux *et al.* 1983; Halpern *et al.* 1984).

Six spectroscopic exposures with the Lick 120-in. Shane telescope and the Miller-Robinson-Stover CCD spectrograph (Miller 1983), and the total integration time of 17 300 s, were obtained on the nights of 26 November, 28 December, and 29 December 1984 UT(KD86). The spectra were extracted and calibrated with the standard procedures (Djorgovski and Spinrad 1983); flux standards of Stone (1977) were used for calibration. The resulting spectrum is shown in Fig. 3.

No strong emission or absorption features (other than the telluric ones) are evident. The limits of equivalent widths of some features of interest are listed in Table I; equivalent widths of the corresponding features in the solar spectrum are also listed, for comparison. HGT85 used photometric colors and absence of prominent absorption features and found that only a star of spectral type G is consistent with their data. Unfortunately, as can be seen from Table I, our additional blue data do not yield any additional information about the nature of the G candidate. Thus we concur with HGT85 that the G candidate is either a very distant main-sequence G star or a nearby cool white dwarf of type DG or DC. The former possibility would immediately exclude the G candidate from being associated with the x-ray source. If the G candidate is a nearby white dwarf, then it is possible that this is the counterpart of the x-ray source in the theoretical models of Arons (1985) and Bisnovaty-Kogan (1985). In this case, the distance of the G candidate is 150 to 250 pc (HGT85).

However, there is some evidence suggesting that 1E 0630 + 178 is no more than 100 pc distant. BCL83 find that for a variety of assumed spectral shapes for the x-ray emission, the x-ray data was best fitted with an $N_{\rm H}$ between 10^{19}–10^{20} cm^{-2} and further specify a firm upper limit of 2×10^{20} cm^{-2}. In the general direction of Geminga, studies of interstellar absorption towards stars (Frisch and York 1983) show: (a) very little neutral hydrogen ($N_{\rm H} < 3\times10^{17}$ cm^{-2}) out to a distance of 75 pc and (b) most stars beyond 75 pc have $N_{\rm H} \sim (1\text{–}5)\times10^{20}$ cm^{-2}. This evidence then favors the interpretation that the G candidate is a distant main-sequence G star. However, maps of the local $N_{\rm H}$ are derived from data towards a modest number of stars. It is possible

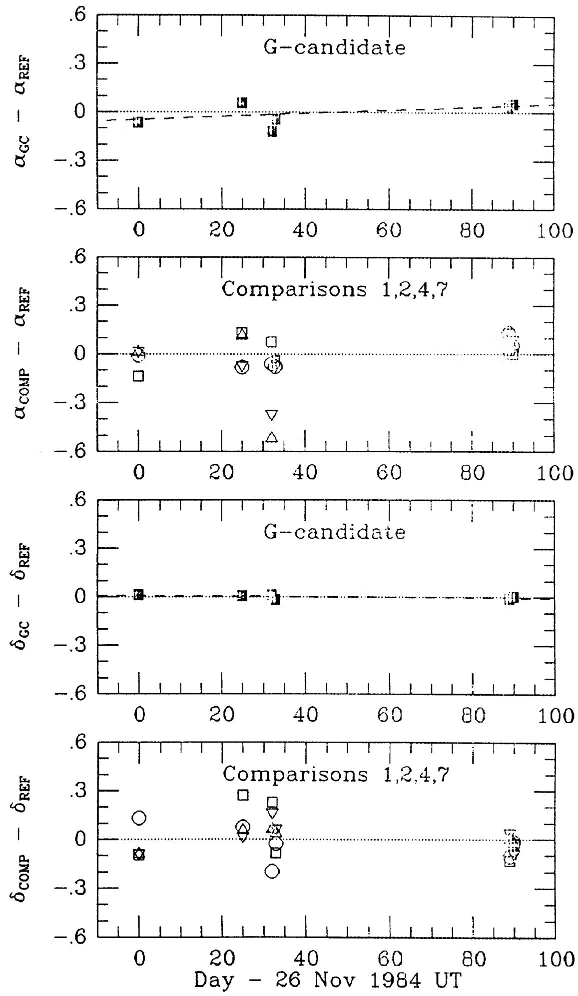

FIG. 2. Relative proper motion of the G candidate and the comparison stars, with respect to the brighter stars in the field. The dashed lines correspond to the least-squares solution described in the text.

that the particular line of sight towards 1E 0630 + 178 is somewhat deficient and consequently the distance to the x-ray source could be as large as 250 pc. Interestingly enough, the lower limit on N_H of 10^{19} cm^{-2} means that *1E 0630+178 cannot be any nearer than* $\sim$*60 pc*. This is a firm limit, since there are *numerous* studies that show that the Sun is immersed in a rarified bubble with a radius $\sim$60 pc. The only uncertainty is whether the BCL83 limit on N_H of 10^{19} cm^{-2} is a true lower limit on N_H.

The spectroscopic evidence, the absence of significant variability and pulsations (Kulkarni and Djorgovski 1985, 1986), the absence of a measurable proper motion (Sol *et al.* 1985; Lecacheux *et al.* 1983; HGT85 and this work), and a discrepancy between the x-ray and the optical position lead us to conclude that the G candidate is probably not the optical counterpart of either the x-ray or the γ-ray source.

Two very faint objects are within the 1E 0630 + 178 error circle (Fig. 1). The brighter one of the two, denoted as the G′ candidate, was also detected by Sol *et al.* (1985), who quote a B magnitude of 24.3 $\pm$ 0.3. In their data, obtained in October 1983, the separation of the two objects was -4.4 ± 0.3 arcsec in α and $+0.4 \pm 0.3$ arcsec in δ (H. Sol, private communication). In our data, obtained in February 1985, we obtain magnitude $r_S = 24.5 \pm 0.5$, suggesting a fairly blue color, and the equatorial position (epoch 1950.0): $\alpha = 06^h30^m59^s\!.006$, $\delta = +17°48'32''\!.39$.

This position was derived relative to the position of the G candidate quoted above, and has the same zero-point errors of 0.4 arcsec in each coordinate. Thus G′ was separated by 5.4 arcsec from G in our February 1985 CCD data, with the separation of -5.35 ± 0.2 arcsec in α, and $+0.45 \pm 0.2$ arcsec in δ. This may constitute a marginal evidence for a proper motion: note that this hinges upon the relative astrometry of two objects close on the sky, and thus it is not subject to the quoted absolute astrometric errors, but only to the centering errors, which are much smaller, typically of the order of 0.1 arcsec per object. However, one nonlinear effect may be important: any spillover light from the brighter object (G candidate) may bias the centering for the fainter one (G′), and the seeing differences may thus produce a spurious position differential. Another problem is that the sky is "bumpy" at these faint magnitudes and low Galactic latitudes, due to the presence of a multitude of fainter, unresolved background stars. For example, the G″ (see below) may be biasing the centering of the G′. Thus the apparent motion in G′ could be either due to a real motion of G′ or that of G″. Future observations should resolve whether this large proper motion is real. It is certainly possible that the G′ candidate is the true optical counterpart of 1E 0630 + 178, and possibly even of Geminga.

Another object, the G″ candidate, about a magnitude fainter than G′, is also present in the x-ray error circle. This object is at the limit of our CCD images. However, there is no doubt about the reality of this star since it is present in two different stacks of images [see also Fig. 1(b)]. The surface density of objects as faint as G′ or G″ at this low Galactic latitude is fairly high, and they can be just chance background stars, superposed on the x-ray error circle. If so, the optical luminosity of 1E 0630 + 178 must be truly extraordinarily low, with apparent visual magnitude fainter than 26, and L_X/L_{opt} ratio in excess of 3000. This would make 1E 0630 + 178 a very unusual object, and corroborate its identification as Geminga.

In Fig. 1(a) we also show the position of a tentative object reported by Bloemen (1984); the error circle shown has a radius that is a compound of ours and his quoted coordinate uncertainties. Nothing is present at this position in our data, down to $r_S = 25.5$.

On the same night (24 February 1985 UT), we have obtained two direct CCD exposures in a 100 Å band centered on Hα, of 1200 s each. The digital stack of the two exposures is shown in Fig. 4. The limiting Hα flux is 24.2 mag/arcsec^2 (3σ limit), corresponding to 0.5 μJy. This translates into a limit of about 5 Rayleigh/arcsec^2, or an emission measure of

TABLE I. Limits to equivalent widths in the G-candidate spectrum and in the solar spectrum.

Feature	λ/Å	W_λ^{lim}/Å	$W_\lambda^{\odot}$/Å
Hγ	4340	$\leqslant$20	~ -2
Hβ	4861	$\leqslant$6	$\sim$3
Hα	6563	$\leqslant$1.2	$\sim$3
CH G band	4217–4403	$\leqslant$60	$\sim$20
Mg, MgH blend	5000–5210	$\leqslant$20	$\sim$2

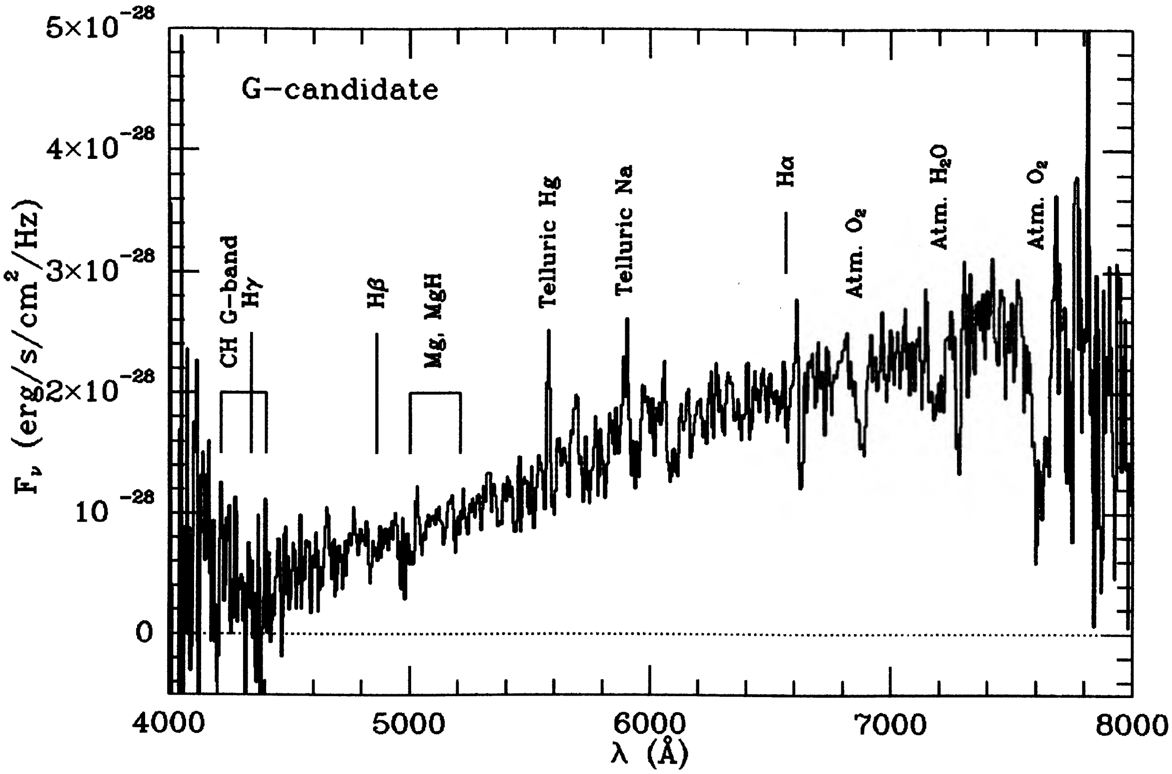

FIG. 3. Spectrum of the G candidate, obtained at Lick. Night-sky features and locations of the tentative stellar features are indicated.

13.5 cm^{-6} pc (in any pixel), assuming an excitation temperature of 10^4 K. We do not see any nebular features on the angular scales covered by our images, viz., from about 1 arcsec to about 1 arcmin. This is a strong limit on the presence of a recent supernova remnant, nova shell, or any other ionized-gas nebulosity in this field. It is possible, in principle at least, that such a nebula may be diluted to much larger angular scales, if it is relatively near.

From considerations of spindown based on the observed x-ray P and $\dot{P}$, Bignami, Caraveo, and Paul (1984) suggest that the event of A.D. 437 (see Zyskin and Mulanov 1983) may have been the precursor of Geminga. Our Hα limits place a severe restriction on the existence of a nebula on scales from a few arcseconds to 2 arcmin around the x-ray source. On the Palomar Sky Survey red print, there is no evidence of nebulosity on larger angular scales; this typically implies an emission measure of less than 50 cm^{-3} pc (Poveda 1963). Taken altogether, these two limits make it unlikely that Geminga is a site of any *recent* injection of a large amount of energy into the ISM. For the conventional supernova remnants, neutral shells start forming at the end of the adiabatic phase (the "snowplow" phase, age $\sim 2\times 10^4$ yr), and only after this time may one then expect to see an H I shell. With this in mind, we have searched through the literature on H I observations, and found no evidence for any expanding H I shell (Heiles 1979 and 1984), or any unusual activity in atomic hydrogen.

Our primary conclusion is that the G candidate is unlikely to be the optical candidate of the x-ray source. This means that the true optical candidate is either G′, G″ or a yet fainter star, not detectable on our deepest CCD image stack. The x-ray spectrum of the source is very soft, with most of the *Einstein* counts below 2 keV and thus $L_x \simeq L_x$ (0.1–2 keV), and is $\sim 2\times 10^{-12}$ erg cm^{-2} s^{-1} (BCL83). L_{opt}, the flux integrated from 3000 to 8000 Å of the G′ candidate, is about 1.8×10^{-15} erg cm^{-2} s^{-1} (Fig. 5); the faintness of G″ precludes any definite measurement, but it is easily a factor of 2 fainter than the G′; any other star fainter than G″ must be at least one magnitude fainter than the G′. Thus L_x/L_{opt} is ~ 1100 if G′ is the correct candidate for 1E 0630 + 178, and about 2500 if G″ is the correct candidate and $\geqslant 3000$ if some other fainter star not detected on our CCD stack image is the correct optical candidate. *It is precisely this conclusion that makes the x-ray source an exciting object, regardless of its association with Geminga.*

As first pointed out by BCL83, the constraint on the distance from the x-ray measurement and the faintness of possible optical candidates rules out the x-ray source being a low-mass x-ray binary. Our results support this conjecture. BCL83 further conclude that the only *known* kind of object that does satisfy all the constraints placed by the observations is a neutron star. Our indicated proper motion of about 0.6 arcsec/yr for the G′ candidate (if real) implies a space velocity of 250 (distance/80 pc) km s^{-1}. This tentative proper motion of G′, if not arising from some unfortunate artifact, supports this idea, and furthermore, it corroborates the hypothesis that *the G′ candidate is indeed the optical counterpart of the x-ray source.* This fits with the neutron-star hypothesis, since it is known that at least pulsars (rotating magnetized neutron stars) have high spatial motion. For

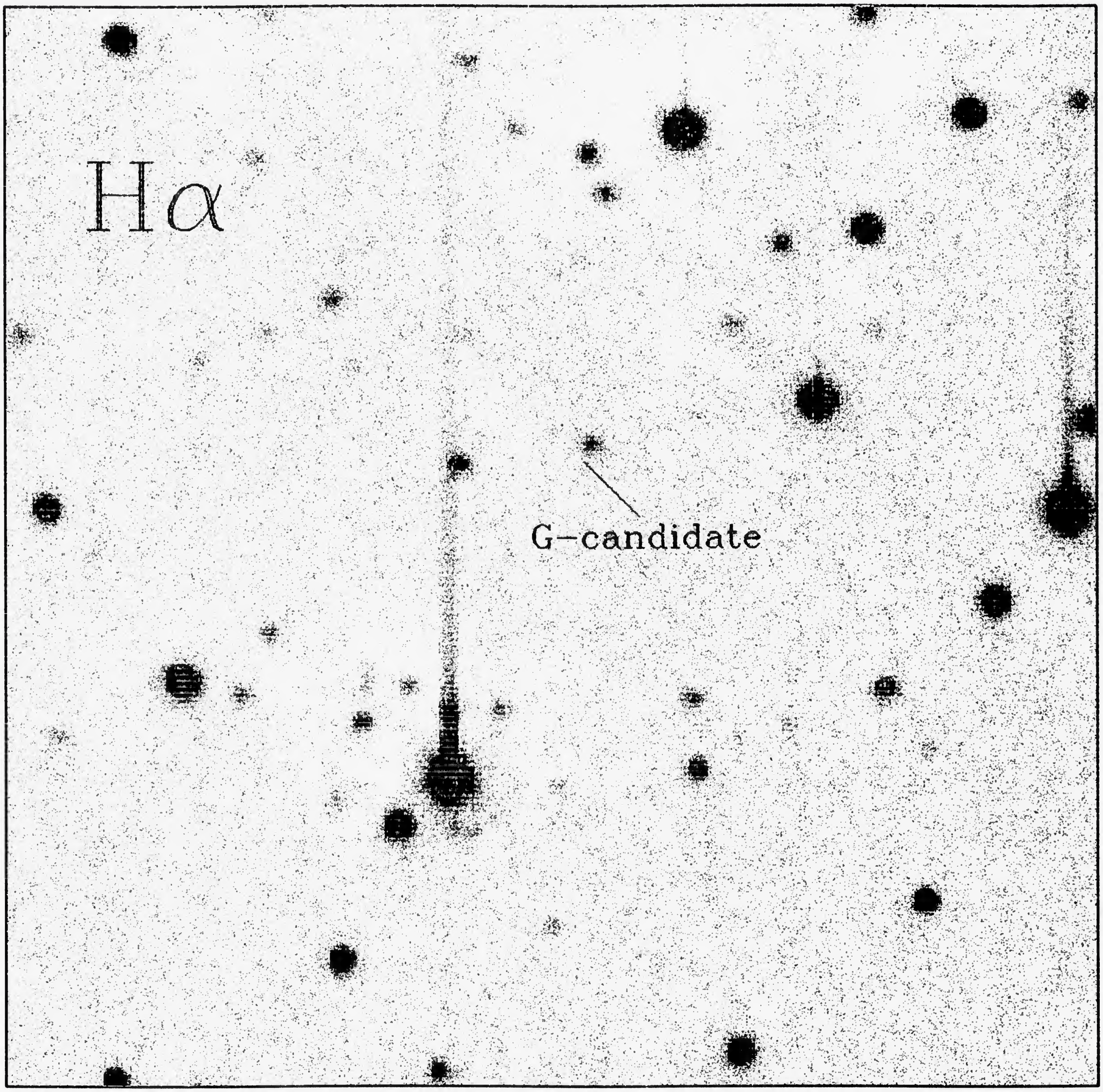

FIG. 4. CCD image stack of the G-candidate field, obtained with the Hα filter. North is up, east to left; the field is 102 arcsec. There is no evidence for any emission-line nebulosity.

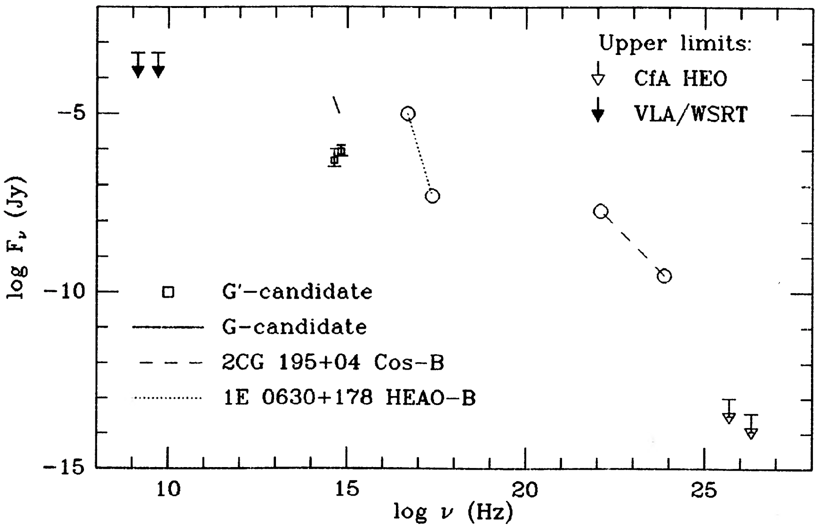

FIG. 5. Flux measurements and limits for Geminga and the objects proposed as its counterparts. The optical data for the G and G′ candidates are from this work, VLA radio limit and *HEAO-B* x-ray data from BCL83, Westerbork (WSRT) radio limit from Spoelstra and Hermsen (1984), *COS-B* γ-ray measurements from Masnou *et al.* (1981), and the Center for Astrophysics High Energy Observatory (CfA HEO) high-energy limits from Helmken and Weekes (1979).

example, about five pulsars have transverse motions in excess of 250 km s^{-1} in the sample of 26 pulsars for which Anderson and Lyne (1985) measured the proper motions. Note that the various constraints discussed earlier do not exclude the possibility that the x-ray source is a double neutron-star binary system (Nulsen and Fabian 1984). Our proper-motion result can easily accommodate such a binary system since, at least the prototype of this model—the binary pulsar system PSR 1913 + 16—is expected to have a large transverse motion of about 170 km s^{-1} (Cordes and Wasserman 1984). Thus, observations allow either model.

Our optical results are consistent with the optical emission arising from thermal emission from a neutron star at a distance of 100 pc, having a 10 km radius, and a surface temperature of 10^6 K. The x-ray flux for the same parameters leads to a temperature of about 3×10^5 K, whereas the x-ray spectrum is best described by a 10^6 K blackbody (BCL83). The higher temperature of 10^6 K is consistent with the detected optical flux from G′, whereas if we believe the lower temperature of 3×10^5 K, then G″ becomes a more suitable counterpart. However, it is important to note that regardless of the optical data, the disagreement of the two x-ray temperatures is a problem for the purely thermal model. In addition, the old age of the neutron-star system as deduced by the absence of any kind of nebula poses additional difficulties for the thermal model. However, if the x-ray source is indeed Geminga, then the thermal model fails completely in explaining the copious γ-ray emission (one thousand times that of the x-ray flux), implying that the dominant energy loss occurs via some nonthermal process—a conclusion independently arrived at by Katz (1985).

We are indebted to Dr. J. Halpern for communicating positions of the field stars for our proper-motion study, and to Dr. H. Sol for communicating the offsets of the G′ candidate. We also thank Drs. J. Halpern, J. Grindlay, G. Bignami, P. Caraveo, and J. Stocke for interesting discussions and communication of prepublication data. This paper benefited from a constructive refereeing by Dr. J. Halpern. Dr. H. Spinrad made generous contributions of observing time at Lick. The solar spectrum used for the comparsion in Table I was kindly communicated by Dr. D. Schleicher. We acknowledge the valuable and competent help of the staff of Lick Observatory, and in particular R. Stone, K. Baker, W. Earthman, J. Morey, B. Alcott, and C. Clark. This work was supported in part by NSF Grant No. AST84-16863, and a University of California Regents Fellowship to S.D.

REFERENCES

Anderson, B., and Lyne, A. G. (1985). Nature **303**, 597.
Arons, J. (1985). Preprint.
Bignami, G. F., Caraveo, P. A., and Lamb, R. C. (1983). Astrophys. J. Lett. **272**, L9 (BLC83).
Bignami, G. F., Caraveo, P. A., and Paul, J. A. (1984). Nature **310**, 464.
Bisnovaty-Kogan, G. S. (1985). Nature **315**, 555.
Bloemen, J. B. G. M. (1984). Astron. Astrophys. **131**, L7.
Caraveo, P. A., Bignami, G. F., Vigroux, L., and Paul, J. A. (1984). Astrophys. J. Lett. **276**, L45.
Cordes, J. M., and Wasserman, I. (1984). Astrophys. J. **279**, 798.
Djorgovski, S., and Spinrad, H. (1983). In *Joint Topical Method on Information Processing in Astronomy and Optics*, St. Paul (American Astronomical Society and Optical Society of America, Washington, DC), p. ThB2-1.
Djorgovski, S., and King, I. R. (1984). Astrophys. J. Lett. **277**, L49.
Djorgovski, S. (1985). Publ. Astron. Soc. Pac. (in press).
Filippenko, A. V., and Greenstein, J. L. (1984). Publ. Astron. Soc. Pac. **96**, 530.
Frisch, P. C., and York, D. G. (1983). Astrophys. J. Lett. **271**, L59.
Halpern, J. P., Grindlay, J. E., Bignami, G. F., and Caraveo, P. A. (1981). IAU Circ. No. 3907.
Halpern, J., Grindlay, J., and Teitler, D. (1985). Astrophys. J. **296**, 190 (HGT 85).
Heiles, C. (1979). Astrophys. J. **229**, 533.
Heiles, C. (1984). Astrophys. J. Suppl. **55**, 585.
Helmken, H. F., and Weekes, T. C. (1979). Astrophys. J. **228**, 531.
Katz, J. I. (1985). Astrophys. Lett. **24**, 183.
Kulkarni, S., and Djorgovski, S. (1985). IAU Circ. No. 4058.

Kulkarni, S., and Djorgovski, S. (1986). Astron. J. **91**, 98 (KD86).
Lecacheux, J., Sol, H., Vanderriest, C., Vigroux, L., Lelievre, G., and Tarenghi, M. (1983). IAU Circ. No. 3892.
Masnou, J. L., *et al.* (1981). 17th I. C. R. C. Paris **1**, 177.
Miller, J. S. (1983). Lick Observatory Internal Report.
Nulsen, P. E. J., and Fabian, A. C. (1984). Nature **312**, 48.
Poveda, A. (1963). Bol. Obs. Tonantzintla Tacubaya **3**, 119.
Sol, H., Tarenghi, M., Vanderriest, C., Vigroux, L., and Lelievre, G. (1985). Astron. Astrophys. **144**, 109.
Spoelstra, T. A. T., and Hermsen, W. (1984). Astron. Astrophys. **135**, 135.
Stone, R. P. S. (1977). Astrophys. J. **218**, 767.
Swanenburg, B. N., Bennett, K., Bignami, G. F., Buccheri, R., Caraveo, P., Hermsen, W., Kanbach, G., Lichti, G. G., Masnou, J. L., Mayer-Hasselwander, H. A., Paul, J. A., Sacco, B., Scarsi, L., and Wills, R. D. (1981). Astrophys. J. Lett. **243**, L69.