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IS GX 1+4 THE COMPACT 511 keV GALACTIC CENTER SOURCE?

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ABSTRACT

An intense 511 keV positron annihilation-line source was detected from the direction of the Galactic center throughout the 1970s. The source disappeared abruptly early in the 1980s. It remained in a low state through at least 1984 and reemerged sometime between 1984 and 1988. This "on-off-on" light curve is mimicked by the X-ray light curve of the pulsating X-ray binary GX 1+4. The similar light curves of the two sources, coupled with their positional agreement and the unusual properties of GX 1+4, suggest that GX 1+4 is the Galactic center positron/511 keV source.

Subject headings: galaxies: nuclei — galaxies: The Galaxy — gamma rays: general — stars: individual (GX 1+4) — X-rays: binaries

I. INTRODUCTION

A 511 keV positron annihilation line has been detected repeatedly from the direction of the Galactic center. The observations to date are summarized below (§ II*a*). For further details see, for example, Ramaty and Lingenfelter (1987) and Leventhal (1987). For the discussion at hand, the relevant observational results are the following: the line is narrow, $\Delta E \lesssim 2.5$ keV FWHM, and unredshifted, $E = 510.90 \pm 0.25$ keV (Riegler *et al.* 1981). In 1979–1980 the 511 keV source dimmed by a factor of 3 in ≤ 6 months, and it appears to have remained in this faint (or "off") state until at least late 1984.[1] In 1988 it was again observed to be in a bright state (Leventhal *et al.* 1989). During the 1970's and in 1988 the 511 keV flux was typically about 1×10^{-3} photons cm^{-2} s^{-1}. The 511 keV flux alone corresponds to a line luminosity of $\sim 7 \times 10^{36}$ $(d/8 \text{ kpc})^2$ ergs s^{-1}, which implies a positron annihilation rate of $\sim 4 \times 10^{42}(d/8 \text{ kpc})^2$ s^{-1}, for an assumed isotropic source. If 100% of these annihilations are via the bound state of Ps,[2] then these numbers are larger by a factor of 4 with the additional luminosity appearing in a three-photon continuum.

The observational results summarized above place the following constraints on the nature of the positron annihilation region. The 6 month intensity variation argues that the size of the region is $\lesssim 10^{18}$ cm ($\lesssim 8''$ at $d = 8$ kpc). The narrow line width ($\Delta E/E < 0.005$) implies that the gas is relatively cool, $T \lesssim 50{,}000$ K. Moreover, the narrow width suggests that the region is fairly homogeneous: If the gas is turbulent or fragmented into cloudlets, the associated velocities are $\lesssim 700$ km s^{-1}. The unshifted central energy of the line implies that the velocity of the emitter with respect to Earth is $\lesssim 200$ km s^{-1} and that the gravitational redshift ($z \approx GM/Rc^2$) in the region is $\lesssim 0.0005$. Current observations do not constrain the ionization state of the annihilation region. The gas may be either cold and neutral or significantly ionized (Brown and Leventhal 1987). There has been considerable theoretical modeling of the 511 keV source. Black hole models with masses between 10 and 10^6 $M_\odot$ have been favored (Lingenfelter and Ramaty 1983; Kardashev *et al.* 1983; Burns 1983; Lingenfelter and Ramaty 1989; Ozernoy 1989), although supernova and pulsar models have also been considered (Colgate 1983; Brecher and Mastichiadis 1983).

The X-ray source GX 1+4 was discovered at high energies ($E \gtrsim 20$ keV) by the M.I.T. Balloon Group in 1970 October (Lewin, Ricker, and McClintock 1971), and was later identified by the *Uhuru* team with the 2–10 keV source 4U 1728−24 (Forman *et al.* 1978). The X-ray source is definitely a neutron star: Its X-ray luminosity is typically $\sim 10^{37}$–10^{38} ergs s^{-1} (for $d = 8$ kpc), and it pulsates periodically with a period of about 2 minutes. GX 1+4 is remarkable in at least three respects: (1) throughout the 1970's it was one of the brightest X-ray sources at high energies ($E \sim 20$–100 keV; e.g., Levine *et al.* 1984), and (for a plausible distance of ~ 8 kpc) it was among the most luminous hard X-ray sources in the Galaxy; (2) it is the only X-ray pulsar located near the Galactic center; and (3) its period derivative is among the largest known for a neutron star. During the 1970's its spin period decreased steadily from about 135 s to 110 s (Elsner *et al.* 1985).

The optical counterpart of GX 1+4 (≡V2116 Oph) was discovered by Glass and Feast (1973). A spectroscopic study by Davidsen, Malina, and Bowyer (1977) revealed high-excitation features (e.g., [Fe VII]) and a late-type (~M6 III) absorption spectrum, which are the defining characteristics of symbiotic stars. Davidsen *et al.* attribute the spectrum to the presence of an envelope of gas around the system with density $\sim 10^9$ cm^{-3} and radius ~4 AU, which is photoionized by the compact X-ray source. The gas is supplied to the neutron star by the massive ($\dot{M} \sim 10^{-6}$ $M_\odot$ yr^{-1}), low-velocity (~10 km s^{-1}) wind of the M giant.

[1] During these 1980–1984 low-state observations, an appreciably higher 511 keV flux was reported by *SMM* (Share *et al.* 1988). This apparent conflict is caused by the very wide field of view of the *SMM* detector (130° FWHM), which views simultaneously the Galactic center source plus a collection of probable (diffuse or discrete) Galactic plane sources (Dunphy, Chupp, and Forrest 1983; Lingenfelter and Ramaty 1989). We do not consider data that have been obtained with wide-field (≥ 50° FWHM) instruments.

[2] Ps (=positronium) is the bound state of a positron and an electron. The $^1S_0$ state decays via two 511 keV photons and the decay of the triplet $^3S_1$ state produces a three-photon continuum.

The infrared continuum spectrum appears to be fairly stable: $K_0 \approx 7.6$ mag and $(J-K)_0 \approx 1.3$ mag, for $E_{B-V} = 1.7$ mag (Glass 1979; Whitelock, Menzies, and Feast 1983; Davidsen, Malina, and Bowyer 1977; Cohen *et al.* 1981). Thus V2116 Oph is somewhat more luminous and slightly redder than a typical M6 giant located in the galactic bulge [$K_0 \approx 8.8$ mag and $(J-K)_0 \approx 1.0$ mag; Frogel and Whitford 1982]. If we (somewhat naively) attribute all of the observed infrared continuum emission to the red giant secondary, then its bolometric luminosity is about -4.4 (cf. Frogel and Whitford 1982). Adopting an effective temperature of 2800 K (Johnson 1966), one finds that the radius of the red giant is $R \sim 1.3$ AU. Although V2116 Oph is an extraordinary optical counterpart of an X-ray source, it is not at all a unique optical/IR object. Over 100 symbiotic stars (including V2116 Oph) have been cataloged by Allen (1984).

Thus the binary GX 1+4/V2116 Oph is composed of an accreting X-ray pulsar that is immersed in the dense wind of its ~M6 III companion. In this paper we suggest that GX 1+4 is the compact 511 keV line source located near the Galactic center. For this to be true, the positional agreement of the two sources is a necessary requirement. The only relatively precise measurement of the position of the 511 keV source was made with *HEAO 3* in the fall of 1979. The 35° (FWHM) detector scanned precisely along the Galactic plane and therefore the data do not provide a useful constraint on b. For a point source, Riegler *et al.* (1981) found $l = 3\overset{\circ}{.}9 \pm 4\overset{\circ}{.}0$, which is entirely consistent with the position of GX 1+4 ($l = 1\overset{\circ}{.}9$, $b = 4\overset{\circ}{.}8$). The positional agreement, although necessary, is not a strong argument for identifying the 511 keV source with GX 1+4. There are, for example, a number of other Galactic-plane X-ray sources consistent with $l = 3\overset{\circ}{.}9 \pm 4\overset{\circ}{.}0$ (see § IIc).

II. OBSERVATIONS

a) The Light Curve of the 511 keV *Line*

All relevant 511 keV line flux data are summarized in Table 1 and plotted in Figure 1*c*. We have omitted data obtained with detector fields of view ≥50° because of the problem of source confusion. As indicated in the table, a small correction has been applied to the observed 511 keV fluxes to take into account the effects of additional diffuse or discrete sources located in the field of view. The magnitude of this correction, 0.8×10^{-3} photons cm^{-2} s^{-1} rad^{-1}, was determined from a Galactic plane observation with the GRIS spectrometer, which was made 25° west of the center ($l = 335°$, $b = 0°$; Leventhal *et al.* 1989). In making the correction, we have assumed that the flux observed in this offset field is the same as the contaminant flux present in the Galactic center.

Some workers have adopted a correction for source confusion (in the Galactic center direction) of $\approx 1.5 \times 10^{-3}$ photons cm^{-2} s^{-1} rad^{-1}, which is about twice the value we have used (e.g., Lingenfelter and Ramaty 1989, and references therein). The value was derived largely using data from wide-field ($\gtrsim 100°$ FWHM) detectors, and it depends on several assumptions, most notably a model of the 511 keV source distribution (Dunphy, Chupp, and Forrest 1983; Share *et al.* 1988; Mahoney 1988) that is in disagreement with the GRIS results mentioned above (see Fig. 3 in Leventhal *et al.*1989). There is another indication that a correction this large may be excessive: If it is applied to the four narrow-field (FWHM ≤ 35°) flux measurements made during the 1980–1985 low state of the compact source, then all the corrected fluxes are negative with confidence levels that range from 0.7 σ to 1.0 σ (see Table 1 in Lingenfelter and Ramaty 1989, col. [5], entries [10], [12]–[13], and [17]). The four measurements combined imply a negative signal at the 2.3 σ level of confidence with an *a priori* probability of occurrence of less than about 2%.

At present, the magnitude of the correction that should be applied for the effect of source confusion is an open question; it is plainly impossible to correct reliably the observed fluxes without knowledge of the distribution of the background sources, which can be deduced only from (presently unavailable) high-angular resolution data. Fortunately, in the case of the Ge spectrometer data (data obtained after 1974), the precise value of the correction is immaterial to our argument because there is agreement on the crucial point: the compact 511 keV source was active during 1977–1979 and quiescent during 1980–1984.

On the other hand, the state of the source (active or

TABLE 1

FLUX MEASUREMENTS AT 511 keV (1970–1988)

Entry Number	Julian Date (2,440,000+)	Calendar Date	511 keV Flux (10^{-3} photons cm^{-2} s^{-1}) Observed	Corrected[a]	Detector	Field of View (FWHM)	Group	Reference
1.........	916	1970 Nov 25	1.8 ± 0.5	1.46 ± 0.5	NaI	24°	Rice	1
2.........	1276	1971 Nov 20	1.8 ± 0.5	1.46 ± 0.5	NaI	24	Rice	1
3.........	2140	1974 Apr 2	0.80 ± 0.23	0.62 ± 0.23	NaI	13	Rice	2
4.........	3459	1977 Nov 11	1.22 ± 0.22	1.01 ± 0.22	Ge	15	Bell/Sandia	3
5.........	3979	1979 Apr 15	2.35 ± 0.71	2.14 ± 0.71	Ge	15	Bell/Sandia	4
6.........	4150	1979 Oct 3[b]	1.85 ± 0.21	1.36 ± 0.21	Ge	35	*HEAO 3*	5
7.........	4319	1980 Mar 20[b]	0.65 ± 0.27	0.16 ± 0.27	Ge	35	*HEAO 3*	5
8.........	4929	1981 Nov 20	0.0 ± 0.6	0.0 ± 0.6	Ge	15	NASA/GSFC	6
9.........	4930	1981 Nov 21	0.0 ± 0.38	0.0 ± 0.38	Ge	15	Bell/Sandia	7
10.........	6025	1984 Nov 20	0.06 ± 0.44	0.0 ± 0.44	Ge	15	Bell/Sandia	8
11.........	7283	1988 May 1	0.98 ± 0.19	0.74 ± 0.19	Ge	17	GRIS	9
12.........	7464	1988 Oct 29	1.23 ± 0.15	0.99 ± 0.15	Ge	17	GRIS	9

[a] An approximate correction for a probable diffuse component of 511 keV emission has been applied; the value, 0.8×10^{-3} photons cm^{-2} s^{-1} rad^{-1} of Galactic longitude, was determined by an observation of the Galactic plane that excluded the Galactic center (§ II*a*; Leventhal *et al.* 1989).

[b] Midpoint of nominal 2 week scan.

REFERENCES.—(1) Johnson and Haymes 1973; (2) Haymes *et al.* 1975; (3) Leventhal, MacCallum, and Stang 1978; (4) Leventhal *et al.* 1980; (5) Riegler *et al.* 1981; (6) Paciesas *et al.* 1982; (7) Leventhal *et al.* 1982; (8) Leventhal *et al.* 1986; (9) Leventhal *et al.* 1989.

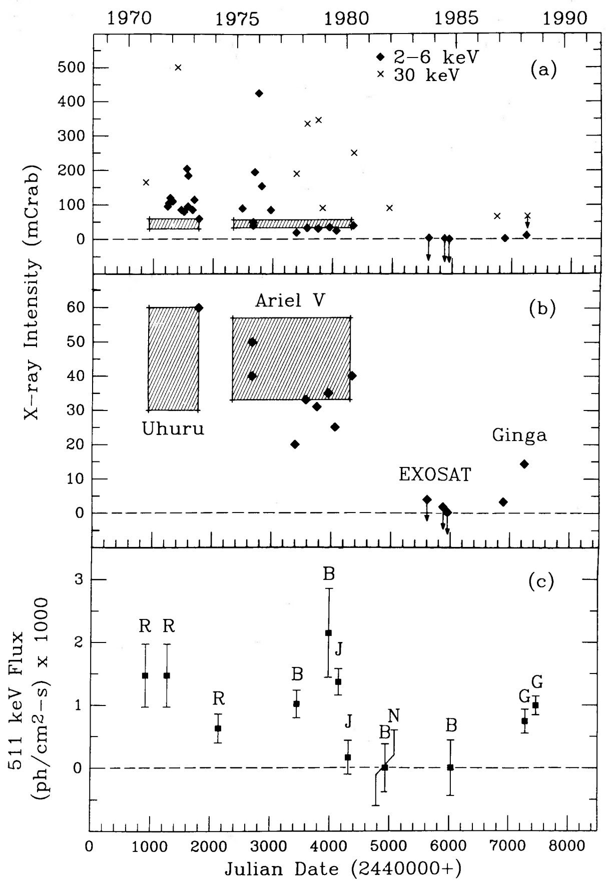

FIG. 1.—The X-ray light curve of GX 1+4 and the 511 keV light curve of the positron-annihilation source in the Galactic center: (*a*) All X-ray data in Table 2 are plotted here. The two cross-hatched rectangles are a summary representation of the *Uhuru* (1970–1973) and *Ariel V* (1974–1980) results; the lower and upper sides of each rectangle represent the minimum and maximum intensities (respectively) measured during the lifetimes of the missions. The statistical uncertainties of the measurements (with few exceptions) are small compared to the size of the plotting symbols. The large scatter in the individual data points is due principally to two effects: (1) variability in the intensity of GX 1+4, and (2) the insoluble problem of properly normalizing results quoted for different broad bandpasses (e.g., 2–6 keV, 1–30 keV, etc.), given a wide range of detector responses and the spectral variability of GX 1+4. (*b*) Same as above except the vertical scale has been expanded so that only intensities $I_X \lesssim 70$ mCrab are shown. Especially evident in this plot are the "turn-off" observed in late 1983 and 1984 with *EXOSAT* (the down arrows are upper limits) and the "turn-on" observed with *Ginga* in 1987 and 1988. (The statistical measurement uncertainties for *EXOSAT* and *Ginga* are minute compared to the size of the plotting symbol.) (*c*) The light curve of the 511 keV Galactic center source. The data and references are given in Table 1: R = Rice, B = Bell/Sandia, J = JPL (*HEAO 3*), N = NASA/GSFC, and G = GRIS.

quiescent) during 1970–1974 remains somewhat uncertain due chiefly to a second effect. The pioneering observations of the Rice University group were made with low-resolution NaI detectors and it is likely that the three-photon (or other) continuum contaminated the line measurements. We have not attempted to correct for this effect because the ratio of the line flux to the three-photon continuum flux is so very uncertain (Brown and Leventhal 1987; Zurek 1985). Lingenfelter and Ramaty (1989) have argued that a maximum downward correction should be applied to the 1970 and 1971 fluxes largely because the observed redshift of the line (476 ± 24 keV) implies that an intense three-photon continuum was present, which they estimate contributed ≈63% of the reported line flux. Their argument, however, is weakened by the 1974 Rice spectrum, which shows a peak at 530 ± 11 keV. No satisfactory explanation for this apparent blue shifted annihilation line has been given, which suggests that the shift was due to an artifact. If so, it seems reasonable to suppose that the redshifted peaks observed in 1970 and 1971 also may have been spurious rather than due to contamination by a three-photon continuum.

With maximal corrections for the effects of a three-photon continuum and source confusion, Lingenfelter and Ramaty (1989) conclude that the compact source was "off" in 1970 and 1971 (and possibly "on" in 1974). We disagree and conclude that the compact source was probably active during 1970–1971 (and 1974). Unfortunately, it appears to be impossible to resolve this disagreement given the sizable uncertainties in the level of the continuum flux and the distribution of background sources; furthermore, it will probably remain an impossibility given the limitations of these early measurements.

Thus we conclude, as summarized in Table 1 and Figure 1*c*, that the data are consistent with a 511 keV source near the Galactic center, which maintained a flux level of about 1×10^{-3} photons cm^{-2} s^{-1} throughout the decade of the 1970's. The abrupt ($\lesssim$6 month) "turn-off" observed in early 1980 established that the source is compact. Three balloon measurements in 1981 and 1984 indicate that the source remained in an "off" state at least until late 1984 November. Sometime between then and 1988 May, the source brightened to the level observed during the 1970's.

In assessing the validity of the above description of the 511 keV light curve, it is important to note that two groups (Bell/Sandia and *HEAO 3*), each equipped with Ge spectrometers, *independently* observed the source "high" in the 1970s and "low" in the early 1980s. Moreover, the 1988 measurements with the GRIS Ge spectrometer, which show the source back "on," are of significantly higher quality than any previous balloon measurement of the 511 keV line.

b) The X-Ray Light Curve of GX 1+4

All of the X-ray data known to us are summarized in Table 2 and plotted in Figure 1*a*. A subset of the data ($I_x < 70$ mCrab) is plotted in Figure 1*b*. We have attempted to put the data from different missions on an equal footing by quoting our best estimate of the intensity of GX 1+4 relative to the Crab nebula. For high energy data (obtained by balloon-borne detectors and some satellites) we quote the relative intensity at 30 keV, and for medium energy data we quote the relative intensity in the canonical *Uhuru* band, 2–6 keV (Forman *et al.* 1978). Because source confusion in the field of GX 1+4 is a significant problem (e.g., see Forman *et al.* 1978), we have included only data obtained with fields of view that are ≤3° (FWHM) in at least one dimension.

The results of the *Uhuru* and *Ariel V* survey missions are globally summarized at the top of Table 2 and in Figures 1*a* and 1*b*. A substantial fraction of the lifetime of these missions was spent scanning the Galactic plane (cf. Jones *et al.* 1976). Both *Uhuru* and *Ariel V* made sensitive measurements of the intensity of GX 1+4 throughout most of the 1970's, and at no time was the source found to be fainter than 30 mCrab. This conclusion is corroborated and strengthened by all other available data gathered for GX 1+4 during the 1970's. These data are summarized in entries (1)–(43) in Table 2. They establish that GX 1+4 shined persistently from the time of its discovery in 1970 October to the last satellite measurement of the decade in 1980 April. During this period, no instrument with the

TABLE 2

X-Ray Intensity of GX 1+4 (1970–1988)

Entry Number	Julian Date (2,440,000+)	Calender Date	X-Ray Intensity (mCrab) ~2–6 keV	~30 keV	Observatory	Reference
4U	933–1760	1970 Dec 12–1973 Mar 18	30 min–60 max	...	*Uhuru*	1
3A	2336–4313	1974 Oct 15–1980 Mar 14	33 min–57 max[a]	...	*Ariel V*	2
1	876	1970 Oct 16	...	165	Balloon (MIT)	3
2	1238	1971 Oct 14	96	...	*OSO 7*	4, 5
3	1259	1971 Nov 4	105	...	*OSO 7*	4, 5
4	1281	1971 Nov 26	120	...	*OSO 7*	4, 5
5	1320	1972 Jan 4	108	...	*OSO 7*	4, 5
6	1413	1972 Apr 5	...	500	Balloon (MIT)	6
7	1466	1972 May 29	86	...	*OSO 7*	4, 5
8	1511	1972 Jul 13	80	...	*OSO 7*	4, 5
9	1558	1972 Aug 29	206	...	*OSO 7*	4, 5
10	1572	1972 Sep 11	94	...	*Copernicus*	7
11	1579	1972 Sep 18	94	...	*Copernicus*	7
12	1581	1972 Sep 21	183	...	*OSO 7*	4, 5
13	1653	1973 Jan 1	83	...	*OSO 7*	4, 5
14	1683	1973 Jan 1	115	...	*OSO 7*	4, 5
15	1767	1973 Mar 25	62	...	*Copernicus*	7
16	2487	1975 Nov 15	80–100	...	*ANS*	8
17	2672	1975 Sep 17	40–60	...	*OSO 8*	9
18	2672	1975 Sep 17	30–45	...	*ANS*	8
19	2696	1975 Oct 10	195	...	*SAS 3*	10
20	2773	1975 Dec 27	425	...	*SAS 3*	10
21	2813	1976 Feb 4	155	...	*SAS 3*	10
22	2964	1976 Jul 4	85	...	*SAS 3*	10
23	3390–3407	1977 Sep 3–20	20	190	*HEAO 1* (MC & A4)	11, 12
24	3572–3590	1978 Mar 4–22	33	335	*HEAO 1* (MC & A4)	11, 12
25	3755–3773	1978 Sep 3–21	31	345	*HEAO 1* (MC & A4)	11, 12
26	3836	1978 Nov 23	...	90	Balloon (AIT/MPI)	13
27	3952	1979 Mar 19	35	...	*Einstein* MPC	14
28	4063	1979 Jul 9	26	...	*Ariel VI*	15
29	4347	1980 Apr 18	38	250	*Ariel VI*	15
30	4941	1981 Dec 2	...	90	Balloon	16
31	5602	1983 Sep 25	<4	...	*EXOSAT*	17
32	5867	1984 Jun 15	<2	...	*EXOSAT*	18
33	5937	1984 Aug 24	<0.4	...	*EXOSAT*	19
34	5940	1984 Aug 27	<0.4	...	*EXOSAT*	19
35	5944	1984 Aug 31	<0.4	...	*EXOSAT*	19
36	5948	1984 Sep 4	<0.4	...	*EXOSAT*	19
37	5952	1984 Sep 8	<0.4	...	*EXOSAT*	19
38	5957	1984 Sep 13	<0.4	...	*EXOSAT*	19
39	6755	1986 Nov 20	...	70 ± 30	Balloon	20
40	6883	1987 Mar 28	3[b]	...	*Ginga*	21
41	6885	1987 Mar 30	3[b]	...	*Ginga*	22
42	7247	1988 Mar 27	14[b]	...	*Ginga*	22
43	7264	1988 Apr 13	...	<70[c]	Balloon	23

References.—(1) Forman *et al.* 1978; (2) Warwick *et al.* 1981; (3) Lewin *et al.* 1971; (4) Markert 1970; (5) Markert *et al.* 1979; (6) Ricker *et al.* 1976; (7) White *et al.* 1976; (8) Parsignault and Grindlay 1978; (9) Becker *et al.* 1979; (10) Doty *et al.* 1981; (11) Levine *et al.* 1984; (12) Remillard 1989; (13) Kendziorra *et al.* 1982; (14) This work; (15) Ricketts *et al.* 1982; (16) Beurle *et al.*1984; (17) Hall and Davelaar 1983; (18) Warwick *et al.* 1988; (19) Mukai 1988; (20) Greenhill *et al.* 1987; (21) Makishima *et al.* 1988; (22) Dotani *et al.* 1988; (23) Cook *et al.* 1989.

[a] The range of intensities given in the 3A catalog for GX 1+4 is 26–46 SSI counts s^{-1} = 65–114 mCrab; the passband is 2–10 keV. In a 2–6 keV band the relative intensity of GX 1+4 is reduced because its spectrum is flatter than the Crab's spectrum. We have (somewhat arbitrarily) corrected for this effect by multiplying the *Ariel V* intensities quoted here by 0.5, which brings the *Ariel V* and *Uhuru* relative intensities for GX 1+4 into agreement.

[b] Intensities inferred from the 2–20 keV luminosities quoted in Dotani *et al.* 1988.

[c] 3 σ upper limit (35–200 keV) based on a preliminary analysis of data obtained with the Caltech imaging γ-ray telescope (GRIP). We have inferred the value of the limit by scaling from the $\approx 6.5\ \sigma$ detection of a source tentatively identified by Cook *et al.* 1989 as 1E 1740.7−2942, which displayed a Crab-like spectrum and had an intensity of about 155 mCrab. We have assumed that the spectrum of GX 1+4 is also Crab-like.

requisite sensitivity and collimation ever found GX 1+4 in a faint state ($I_x \lesssim 20$ mCrab), and more than a dozen such instruments made repeated observations throughout the decade.

A balloon measurement of the intensity of GX 1+4 was made on 1981 December 2 (Beurle *et al.* 1984). The reported intensity is $I_x \approx 90$ mCrab at 30 keV (Table 2, entry [30]). This is a key observation because it occurred well into the low-state epoch of the 511 keV source. A strong confirmation of this important result probably could be achieved by performing a Fourier/folding analysis, on the pulsed component of the X-ray flux, which apparently has not been done.[3]

[3] Another possible balloon detection (3.2 σ) of the pulsed flux (at $E > 180$ keV) was made during the low state of the 511 keV source on 1982 April 12 (Jayanthi, Jablonski, and Braga 1987). Two other balloon observations in 1984 did not achieve credible detections of either the pulsed or DC components of the flux (see Manchanda 1988, and references therein).

The next reported observations of GX 1+4 were made on 1983 September 25 by the *EXOSAT* Observatory (see Table 2, entry [31]) with a detector substantially more sensitive than any that had been used previously to observe the source. *EXOSAT* failed to detect GX 1+4 during a 13 hr pointed observation! The intensity of the source was (very conservatively) quoted as less than 4 UFU $\approx$ 4 mCrab (Hall and Davelaar 1983). Similarly, scanning observations with *EXOSAT* in 1984 mid-June also failed to achieve a detection ($I_x < 2$ mCrab; Warwick *et al.* 1988).

Ten weeks later Keith Mason reobserved GX 1+4 with *EXOSAT*. He made six observations over a 2 week interval (Table 2, entries [33]–[38]); care was taken to minimize systematic errors in the measurement of the background flux. Again, no DC or pulsed flux was observed from GX 1+4. The following conclusion was reached after a thorough analysis, which accounted for the effects of faint, unresolved sources in the Galactic plane: "A reasonably secure limit to the X-ray radiation from GX 1+4 during these six observations is 7.1×10^{-12} ergs cm^{-2} s^{-1}" in a 2–7 keV band (Mukai 1988). This flux limit corresponds to a relative intensity of 0.4 mCrab. Thus, on six occasions in 1984 August/September GX 1+4 was approximately 50 times fainter than the *minimum* intensity that it maintained throughout the 1970s.

GX 1+4 was next observed in 1987 March by *Ginga*, a proportional counter array of unprecedented sensitivity. During two pointed observations ($T_{obs} \approx 12$ hr), GX 1+4 was "unambiguously detected" at a mean intensity of about 3 mCrab, and the characteristic 2 minute pulsations were impressively recorded (Makishima *et al.* 1988; Dotani *et al.* 1988). One year later, 1988 March 27, GX 1+4 was reobserved with *Ginga* and found to have brightened further to approximately 14 mCrab (Dotani *et al.* 1988).

In summary: Throughout the 1970s GX 1+4 was observed frequently and its intensity was never found to be below about 20 mCrab. In 1983 September, 1984 June, and 1984 August/September, *EXOSAT* failed to detect GX 1+4; in particular, in 1984 the source was $\gtrsim 50$ times fainter than it was at any time during the 1970's. By 1987 March the source had reappeared at an intensity of about 3 mCrab, and by 1988 March it had brightened further to about 14 mCrab.

c) *The X-Ray Light Curves of Other X-Ray Sources*

As noted at the end of § I, there are a number of Galactic plane X-ray sources with positions that are consistent with the Galactic longitude of the 511 keV source: $-4°.1 < l < 11°.9$ ($\pm 2\ \sigma$; Riegler *et al.* 1981; Fig. 2). Here we consider the light curves of these sources, excluding short-lived ($\lesssim 1$ yr) transient sources (e.g., H1705−250, H1743−322, etc.), and conclude that (with the possible exception of 1E 1740.7−2942) only GX 1+4 has mimicked the "on-off-on" behavior of the 511 keV source.

Consider first the sources that lie outside the confused 1° diameter region at the Galactic center. The following is a complete list of all such sources that were persistently bright during the period 1977 November–1979 October when the 511 keV source was definitely bright: GX 1+4, GX 3+1, GX 5−1, GX 9+1, GX 9+9, 4U 1755−33, 4U 1822−37, and 4U 1820−30 (Warwick *et al.* 1981; Levine *et al.* 1984; Wood *et al.* 1986). During the 1980 March–1984 November low state of the 511 keV source, only GX 1+4 turned "off"; the other seven sources remained bright (Schulz, Hasinger, and Trümper 1988,

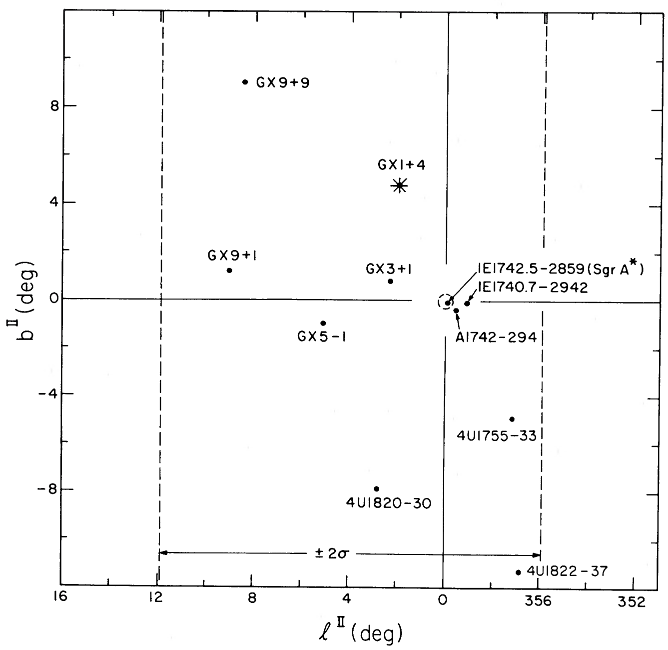

FIG. 2.—A $\pm 2\ \sigma$ bound on the longitude of the 511 keV source is indicated by the dashed lines; the most probable longitude is $l = 3°.9$, and the latitude is only roughly constrained by the 15° (FWHM) balloon experiments. The locations of the compact X-ray sources discussed in the text are shown. The 40′ diameter circle at the Galactic center contains 11 faint sources, only one of which is plotted here (see Watson *et al.* 1981). Note that the positions of GX 1+4 and the 511 keV source are entirely consistent.

and references therein; White *et al.* 1984; White and Mason 1985; Sternberg *et al.* 1986).

Consider now the nest of sources located within 20′ of the Galactic center, including the source 1E 1742.5−2859, which is probably associated with Sgr A*. On 1979 March 7 and 1979 September 20, during the "on" state of the 511 keV source, all 11 of these sources were very faint ($L_x \leq 1.0 \times 10^{35}$ ergs s^{-1} for $d = 8$ kpc, as inferred from observations in the 0.9–4.0 keV *Einstein* IPC band) compared to any of the sources mentioned above (Watson *et al.* 1981). Moreover, the combined 2–6 keV intensity of these 11 point sources, which was measured simultaneously with the 0°.75 (FWHM) MPC detector, was much less than the observed intensity of 25 mCrab, which was entirely accounted for by the expected contributions from a diffuse central source plus an extraneous point source located 30′ from the Galactic center (Watson *et al.* 1981). Based on the available X-ray data, we conclude that none of these undistinguished sources is a likely counterpart of the 511 keV source. We note that Kawai *et al.* (1988) found 1E 1742.5−2859 (Sgr A*) in a low state in 1985 June (when the 511 keV source was probably "off") and mention that this lends support to the idea that the 511 keV source is associated with Sgr A*. However, their suggestion was undercut by observations made 6 weeks later that showed 1E 1742.5−2859 to again be bright (Skinner *et al.* 1987; Skinner 1988).

A persistent and intense flux of hard X-rays ($E > 20$ keV), which comes from within 2° of the Galactic center, has been observed on many occasions (e.g., Levine *et al.* 1984). Unfortunately, the record of observations of this region at $E \gtrsim 20$ keV is murky because of source confusion caused by a combination of source crowding and the generally poor angular resolution of high-energy detectors. During the 1970's, the best angular resolution at high energies was achieved with the *HEAO 1* A-4 experiment. Its 1°5 × 20° (FWHM) crossed-slat detectors definitely localized the hard source (hereafter referred to as HGCX) to within 2° of the Galactic center (Levine *et al.* 1984).

Today there are two leading candidates for the medium-energy (2–10 keV) counterpart of HGCX, A1742−294 and 1E 1740.7−2942 (e.g., see Skinner *et al.* 1987, and references therein). They are separated by 32′ and have precise (1′) positions. Unfortunately, the 1°5 (FWHM) resolution of *HEAO 1* A-4 does not allow one to distinguish between A1742−294 and 1E 1740.7−2942 because of the effects of source confusion and source variability, which force one to introduce a complex model into the analysis (A. Levine, private communication; also, see Matteson 1982). We note that some other observers claim to have localized HGCX to higher precision using even wider field 5° (FWHM) detectors (e.g., Dennis *et al.* 1980; Knight *et al.* 1985); however, the interpretation of these data is severely model-dependent and the conclusions must be viewed as uncertain for the reasons just stated.

We now discuss in turn A1742−294 and 1E 1740.7−2942, the two candidate counterparts of HGCX: A1742−294 is located 0°6 from the Galactic center. It was discovered as a "transient" (or new) source in data obtained on 1976 March 22 (*Ariel V* Group 1976), although it actually appeared somewhat earlier in mid-1975 (Jernigan *et al.* 1978). Since the source's emergence, every medium-energy (2–10 keV) observation with good angular resolution has shown the source to be active (see Skinner *et al.* 1987, and references therein; Warwick *et al.* 1988; Remillard 1989).

Recent observations (in 1985 and 1988) of 1E 1740.7−2942 at high energies and with high angular resolution showed this medium-energy source to have a harder spectrum than A1742−294 (Skinner *et al.* 1989; Cook *et al.* 1989). The source 1E 1740.7−2942, which is located 0°9 from the Galactic center, was discovered in an *Einstein* IPC observation made on 1979 September 21 (Hertz 1983; Hertz and Grindlay 1984). At medium energies, 1E 1740.7−2942 is 2–5 (or more) times fainter than A1742−294 (Hertz and Grindlay 1984; Skinner *et al.* 1987; Kawai *et al.* 1988; Remillard 1989), whereas, at high energies (>20 keV) it can be much brighter than A1742−294 (Skinner *et al.* 1987; Cook *et al.* 1989). These recent results suggest that the hard galactic center source observed earlier with *HEAO 1*, *OSO 8*, etc. may be 1E 1740.7−2942, rather than A1742−294; however, this conclusion is far from certain given the likelihood of source variability and the limitations of the earlier high-energy work.

In summary, there is definitely a bright, hard X-ray source located within 2° of the Galactic center that has been observed repeatedly since 1977. We assume that the medium-energy counterpart of HGCX is either 1E 1740.7−2942 or A1742−294. Given the large uncertainties, what can be said about the possibility that HGCX is the 511 keV/positron source instead of GX 1+4?

There are several reasons we favor GX 1+4 over A1742−294 and 1E 1740.7−2942 (i.e. HGCX): ruling against A1742−294 is easy. In 1984 June, when the 511 keV source was definitely "off," A1742−294 was "on" ($I_x \approx 90$ mCrab; Warwick *et al.* 1988). On the other hand, the intensity of 1E 1740.7−2942 during the "off" state epoch of the 511 keV source is uncertain. The only observation occurred in 1984 June (Warwick *et al.* 1988); the source is not listed in Table 2 in Warwick *et al.*, and it is not apparent in their contour map, which suggests that it may have been "off" or faint. However, the source could have been about one-tenth as bright as A1742−294—i.e., faint but "on"—and still have escaped detection due to source confusion (R. Warwick, private communication). During the scan crossings of 1E 1740.7−2942, there were multiple sources in the *EXOSAT* 45′ (FWHM) field of view; in particular, 1E 1740.7−2942 and A1742−294 were separated by only 26′ in scan angle. Thus we cannot rule on whether 1E 1740.7−2942 was "on" or "off" when the 511 keV source was "off". (We note, however, that 1E 1740.7−2942 was definitely "on" in 1985 June (Kawai *et al.* 1988) and in 1985 July/August (Skinner *et al.* 1987), not long after the last "off"-state measurement of the 511 keV source.) In short: We favor GX 1+4 over 1E 1740.7−2942 because during the 511 keV "off-state" GX 1+4 was definitely "off" on eight occasions in 1983–1984, whereas 1E 1740.7−2942 may have been either "on" or "off."

There are three additional arguments that weigh in favor of GX 1+4.

1. During 1970–1974, when the 511 keV source was probably "on" (§ II*a*), 1E 1740.7−2942 (and A1742−294) went unreported and was therefore "off" or very faint (Kellogg *et al.* 1971; Forman *et al.* 1978; Markert *et al.* 1979).
2. The 511 keV flux of 1E 1740.7−2942 was less than 0.8×10^{-3} photons cm^{-2} s^{-1} (preliminary 99% confidence) on 1988 April 12 (Cook *et al.* 1989), at a time when the Galactic center 511 keV source was almost certainly active (cf. Table 1).
3. The *HEAO 3* position of the 511 keV source ($l = 3°9 \pm 4°0$) is in better agreement with the position of GX 1+4 ($l = 1°9$; 0.5 σ) than with the position of 1E 1740.7−2942 ($l = 359°1$; 1.2 σ).

III. DISCUSSION

The case that GX 1+4 is the compact source of annihilation-line radiation rests squarely on the similarity between the X-ray and 511 keV light curves, which span 18 yr: both GX 1+4 and the 511 keV source were observed frequently throughout the 1970's, and both sources were always found to be bright.[4] By 1980 March 20, the 511 keV source dimmed by a factor of 3. From then until the time of *EXOSAT* there were only two credible X-ray observations known to us that showed GX 1+4 in an "on" state.[5] The first of these occurred about 4 weeks later and showed the source bright at both medium (2–6 keV) and high (30 keV) X-ray energies; thus GX 1+4 appears to have turned "off" somewhat later than the 511 keV source. The second observation occurred well into the low-state epoch of the 511 keV source on 1981 December 2, and it was made at *high X-ray energies* ($E > 20$ *keV*). Two weeks earlier, and also in 1984 November, the Galactic center was observed 3 times with sensitive Ge detectors, and no 511 keV radiation was detected—a result of exceptional interest to γ-ray astronomers. Similarly, in 1983 September, 1984 June and 1984 September, *EXOSAT* failed to detect GX 1+4, which was a notable event to X-ray astronomers. By the end of 1987 March, GX 1+4 had reappeared in a faint state. A year later (1988 March 27) the X-ray source had become ≥35 times

[4] As discussed in § II*a*, the 511 keV line flux measurements for 1970–1974 are uncertain, and our contention that the source was bright then is disputed.

[5] Possibly the *Hakucho* Observatory, which was launched on 1979 February 21, observed GX 1+4; however, its capability for observations of GX 1+4 was probably marginal and we found no observations reported in the literature.

brighter than it was during the "off" state observed with *EXOSAT*, although it was still fainter than the minimum level it had maintained throughout the 1970's. One month later (1988 May 1), the 511 keV source was observed to have brightened to its 1970–1979 intensity level, and 6 months later it was again observed to be in its high-intensity state. The only (reported) X-ray intensity measurement of GX 1+4 since the 1988 May 1 discovery of the 511 keV "turn-on" is a high-energy (35–200 keV) upper limit of 70 mCrab (Cook *et al.* 1989; see Table 2). This result suggests that GX 1+4 may not have brightened fully to the level of the 1970's, although the limit is too weak to permit a definite conclusion.

Thus both the 511 keV source and GX 1+4 were "on" throughout the 1970's, "off" during the early mid-1980's, and "on" again in 1987–1988. This correlated "on-off-on" behavior is the crux of our argument that GX 1+4 is the compact positron/511 keV source. The above argument is buttressed significantly by the following circumstantial evidence (see also § I):

1. The hard X-ray spectrum ($E \sim 20$–200 keV) of GX 1+4 has been noted in the literature often as an anomaly ever since its 1970 discovery. This hard spectrum—observed for only a few percent of X-ray binaries—distinguishes GX 1+4, and thereby makes it more plausible to link this source to a unique compact positron source.

2. The symbiotic optical spectrum is a second distinctive quality of this system. The M giant secondary, its low-velocity wind, and the high-excitation nebula that surrounds the system are unique features of this X-ray binary, and they are also plausible sites for positron annihilation.

3. Throughout the 1970's, the X-ray pulsar spun up steadily from 135 s to 110 s. A unique and long-term spin-*down* episode has occurred since the time of the X-ray turn-off (Makishima *et al.* 1988; Manchanda 1988; Dotani *et al.* 1988), and only exotic and ad hoc explanations have been advanced to explain it: White (1988) has invoked an extraordinary pulsar magnetic field ($B \sim 10^{14}$ G), whereas Dotani *et al.* (1988) favor a retrograde accretion disk model. In any case, the spin-down event again sets GX 1+4 apart from other X-ray binaries.

4. Two additional anomalies single out GX 1+4: The 1987–1988 X-ray pulse profile is "very peculiar ... such a pulse profile has never been observed previously, suggesting that some drastic change has occurred in the system" (Dotani *et al.* 1988). Also, major disturbances in the spectrum of the optical counterpart have been noted since the time of the X-ray turn-off (Whitelock, Menzies, and Feast 1983; Whitelock 1984; Gotthelf, Halpern, and Szentgyorgyi 1988; Dotani *et al.* 1988).

5. Finally, GX 1+4 is the only X-ray pulsar in the vicinity of the Galactic center. (The second closest, OAO 1653−40, is located at $l = 344°$, $b = 0°$; Joss and Rappaport 1984, and references therein; Stella, White, and Rosner 1986). The arguments given above are the sum of the evidence that GX 1+4 is the Galactic center positron/511 keV source.

We note that a recent model for the *diffuse* 511 keV Galactic plane emission (Kluzniak *et al.* 1988), which invokes a collection of weakly magnetized and rapidly rotating neutron stars, is not directly applicable to GX 1+4 (which is a strongly magnetized slow pulsar). Similarly, models constructed to explain TeV γ-radiation from X-ray binaries or the vacuum electrodynamics of radio pulsars are also not directly relevant. We do not suggest a mechanism for generating positrons; we simply state that the rotating neutron star and its magnetic field are the only plausible source of the positrons if GX 1+4 is the compact 511 keV source.

Almost certainly a positron will leave the vicinity of the neutron star (traveling along a magnetic field line) with a kinetic energy $\gtrsim m_e c^2$; consequently, a few g cm^{-2} of material are required to thermalize the positron, a process that occurs prior to either free annihilation or annihilation via the bound state of Ps (Crannell *et al.* 1976; Bussard, Ramaty, and Drachman 1979). The 511 keV line cannot be formed very near or in the photosphere of the neutron star because it is unredshifted. Possible annihilation sites that may satisfy the observational constraints on the width, central energy, and luminosity of the 511 keV line (see § I) are the following: (1) the accretion flow beyond the magnetosphere of the X-ray pulsar; (2) the wind of the M giant, if it is sufficiently dense; and (3) the photosphere of the M giant (the positron flux at the M giant is probably enhanced by the transport of positrons along pulsar field lines that thread the giant star; cf. Lamb *et al.* 1983.)

We now mention two possible explanations for the 1980–1985 low state of the X-ray/511 keV source. First, it is tempting to think that the X-ray source was eclipsed by its giant companion. During such an eclipse the positron-irradiated face of the giant star would be turned away from us and the 511 keV source might therefore be dim. The indicated orbital period is $\gtrsim 18$ yr, and the corresponding separation between the stars is $\gtrsim 9$ AU (for a minimum total system mass of $\sim 2.5\ M_\odot$). A difficulty with this picture is the smallness of the solid angle subtended by the M giant ($\Omega/4\pi \lesssim 0.005$ for $R \sim 1.3$ AU; see § I), which implies a small *a priori* probability of an eclipse ($\lesssim 13\%$), and also might require that the positron luminosity significantly exceed the Eddington luminosity of the compact object, if the annihilation region is the star's photosphere. A second explanation for the 1980–1985 low state is an episodic ejection of mass from the M giant that smothered the X-ray source and spun down the pulsar (Manchanda 1988); presumably such an event might smother or turn off the positron source as well. We favor Manchanda's hypothesis because there is good evidence that hard X-rays were detected during the "off" state of the 511 keV source (Beurle *et al.* 1984; § II*b*), and because of the large column density of absorbing matter observed in 1987 March with *Ginga* (Dotani *et al.* 1988).

We conclude by noting that a single observation with a coded-aperture or tightly collimated detector could clinch our argument that GX 1+4 is the compact 511 keV source in the Galactic center. GX 1+4 is located 5° from Sgr A*, and therefore a $\sim 1°$ position for the 511 keV source would be decisive. If GX 1+4 is the positron source, then many promising observations come to mind. Of central importance would be the frequent monitoring of the hard X-ray/511 keV flux with the GRO/OSSE detector and with the Ge spectrometer on the proposed NAE Observatory.

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