THE ASTROPHYSICAL JOURNAL, 410:110–115, 1993 June 10

VLA OBSERVATIONS OF 1E 1740.7−2942: A SEARCH FOR RADIO RECOMBINATION LINES OF POSITRONIUM

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Received 1992 July 20; accepted 1992 December 10

ABSTRACT

We have searched for the Ps87α ($\nu_{\rm rest} = 4911.105$ MHz) recombination line of positronium at the position of the *Einstein* X-ray source 1E 1740.7−2942 which has been identified as a strong source of time-variable annihilation line radiation. No line was detected with a 3 σ upper limit of 330 μJy for a line width of 23.5 MHz, the expected width if the temperature of the annihilation region is $\sim 7 \times 10^4$ K. A continuum image of the field made from the same data shows, within the 90% confidence error circle of the X-ray source, a weak radio source with a core and lobe structure similar to extragalactic double radio sources. Comparison with other observations shows that the radio flux density of the core at 6 cm had increased by a factor of ≈ 2.6 between 1991 October 7 and November 16 and has been decreasing steadily since then. We have explored some possible relations between the radio source and the X-ray source. We find that the radio and the X-ray sources could well be associated with each other. The nature of this source is uncertain—it could be either Galactic or extragalactic. In either case this source is a unique object.

Subject headings: black hole physics — elementary particles — Galaxy: center — gamma rays: observations

1. INTRODUCTION

There has been considerable interest in the *Einstein* X-ray source 1E 1740.7−2942 since it was recently identified with the time-variable positron electron annihilation-line radiation which originates from the vicinity of the Galactic center (Bouchet et al. 1991; Sunyaev et al. 1991a, b). The 0.5 MeV narrow annihilation-line radiation was observed during the 1970s in a number of balloon and satellite experiments (see MacCallum & Leventhal 1983); because of the low angular resolution of the detectors, the location of the source was known only to within a few degrees. From the nature of the line radiation and the accompanying lower energy continuum, it has been suggested that the object could be a black hole of stellar mass (Lingenfelter & Ramaty 1989). With the advent of the coded aperture mask techniques which give angular resolution of the order of 1′ at hard X-ray energies ($E > 20$ keV), several individual sources in the vicinity of the Galactic center have been identified (Skinner et al. 1987; Cook et al. 1991; Sunyaev et al. 1991a, b). Among these, the strongest source in the energy band 35–120 keV is 1740.7−2942, which is positionally coincident with the *Einstein* source located about 0°.9 southwest of the Galactic nucleus at $l = 359°.1$ and $b = -0°.1$. Recent observations by the coded aperture high-energy telescope SIGMA on board the *GRANAT* space observatory have revealed the source 1E 1740.7−2942 to be unique in that it exhibited a remarkable broad line feature near 0.5 MeV on 1990 October 13 (Mandrou et al. 1990; Bouchet et al. 1991) which can be attributed to the annihilation of positrons and electrons. The duration of the event has been estimated to be between 18 and 70 hr, which sets an upper limit of $\sim 10^{15}$ cm for the dimensions of the source (Bouchet et al. 1991). Subsequent observations by the SIGMA telescope have established that 1E 1740.7−2942 has three spectral states at X-ray energies: the normal state in which the spectrum is similar to that of Cyg X-1, the hard state which is accompanied by the broad annihilation line radiation, and a low state in which the luminosity in the 35–100 keV band is about a factor of 5 less than the normal state (Sunyaev et al. 1991a, b). On the basis of the similarity of the spectrum to Cyg X-1, the time variability at hard X-ray energies, and the occurrence of the transient broad annihilation line, it has been suggested that 1E 1740.7−2942 could be a stellar mass black hole powered by accretion (Cook et al. 1991; Sunyaev et al. 1991a, b; Bouchet et al. 1991). This suggestion seems to have been strengthened by the discovery of an associated dense molecular cloud which could provide the necessary material for accretion (Bally & Leventhal 1991; Mirabel et al. 1991a).

It should be pointed out here that there are two serious difficulties in identifying the X-ray source 1E 1740.7−2942 as the source of the narrow annihilation line observed from the Galactic center region in several balloon flights between 1970 and 1980 and again in 1988 (Geherls et al. 1991). The first difficulty is that the line feature observed from 1E 1740.7−2942 on 1990 October 13–14 cannot be satisfactorily fitted with a pure positronium spectrum consisting of an unredshifted narrow feature at 511 keV due to two-photon annihilation and a broad continuum due to three-photon annihilation (Bouchet et al. 1991; Sunyaev et al. 1991a, b). This suggests that the line feature may indeed be due to "in flight" annihilation of positrons in a "hot pair" plasma as discussed by Ramaty & Meszaros (1981). The shift of the line center to lower energies can then be due only to redshift, perhaps cosmological. The second difficulty is that, if the line feature is variable on the time scale of a day, as observed in 1E 1740.7−2942, then it is remarkable that *all* eight balloon measurements performed between 1970 and 1979 (see Fig. 1 in Lingenfelter & Ramaty 1989) detected the narrow annihilation line with an intensity within a factor of 3 or so. These difficulties suggest that the narrow annihilation line detected toward the Galactic center may not be related to the X-ray source 1E 1740.7−2942.

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Searches have been made for a possible radio counterpart of 1E 1740.7−2942. Using data at 20 and 6 cm obtained with the Very Large Array (VLA) in 1989 March, Prince & Skinner (1991) have detected two radio sources within the *Einstein* error circle, which they referred to as sources A and B (Fig. 1). They have suggested that source A, because of its pointlike nature, is the more likely counterpart of 1E 1740.7−2942. A third source C is present in the vicinity (Leahy 1991), but it is outside the error circle of 1E 1740.7−2942. Gray, Cram, & Ekers (1992) have reported detection of sources B and C; due to their sensitivity limit they did not detect source A. Mirabel et al. (1991b), in their radio observations during 1991 September and October (which were coordinated with SIGMA and *Gamma Ray Observatory*), detected both sources A and B and found source A to be variable. Since then, they have monitored the flux density of source A over the period 1992 January–April. More recently Mirabel et al. (1992a, b) have reported that source A is located at the center of an aligned double radio jet and that source B appears as a hot spot at the end of the northern jet. They find that the changes in the flux density of source A are correlated with variations in the hard X-ray output. They suggest that 1E 1740.7−2942 is a "microquasar" stellar remnant near the Galactic center.

In this paper we report the results of our observations of this source performed on 1991 November 16 and 17 at a wavelength of 6 cm using the VLA in its B-configuration. These dates were chosen because the OSSE on board the *Gamma Ray Observatory* was also scheduled to observe the Galactic center region on these dates. Our observations were aimed at the detection of possible radio recombination lines of positronium which might be formed prior to the annihilation of positrons and electrons (McClintock 1984; Anantharamaiah et al. 1989). The possibility of observing these lines was, of course, contingent on whether or not the source would be in a high state similar to that observed on 1990 October 13–14. As it turned out, the source was not in a high state and no lines were detected; however the data collected could also be used to form sensitive continuum images of this region. These images have about the same sensitivity ($\approx 40\ \mu$Jy beam^{-1}) as the 6 cm images made by Mirabel et al. (1992b) but have better resolution ($\approx 2''$) by a factor of 2. In these continuum images, both sources A and B mentioned above were detected along with an additional component which seems to suggest that the three components may form a single connected radio source. In addition, by combining our observations with those of Mirabel et al. (1992b), we have also detected a rapid rise in the flux density of source A during 1991 October–November. In the following sections we present the details of the observations, the limits on the strength of the recombination line and its implication, and discuss the possible relationship between the X-ray and radio sources.

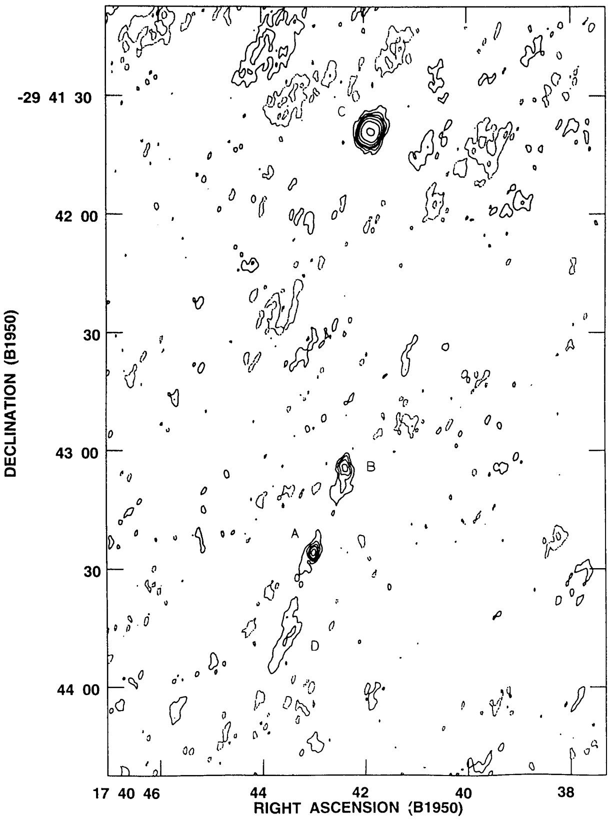

FIG. 1.—5 GHz continuum image of the field containing 1E 1740.7−2942. The angular resolution is $2''.6 \times 1''.6$ (PA = −15°). The contours are at −150, −90, 90, 150, 210, 270, 390, 600, 1200 μJy beam^{-1}. The rms noise is 40 μJy beam^{-1}.

2. OBSERVATIONS AND DATA PROCESSING

The observations were made for 7.5 hr on the 16th and 4.5 hr on the 17th of 1991 November. The VLA was in its B-configuration which gave a resolution of $2''.6 \times 1''.6$ (PA = −15°) at 6 cm. Within any frequency band of operation (e.g., 4.5 to 5.0 GHz in the 6 cm band), the VLA receiver system can be used to provide simultaneous data from two independently tunable ratio frequency bands. We used two such settings in spectral line mode, and alternated between them every half-hour to collect data in three adjacent bands of 25 MHz each, separated by 15.625 MHz. The three bands were centered at 4895.4806, 4911.1056, and 4926.7300 MHz. The central band corresponds to the rest frequency of the positronium 87α line. The first two bands were observed in one setting and the last two in the second. The central band was therefore observed during both settings. Each band was observed with 8 spectral channels resulting in a frequency resolution of 3.125 MHz (≈ 191 km s^{-1}). Between the adjacent bands there was an overlap of two channels. This enabled precise calibration of the three bands by matching the observed intensities in the overlapping regions. Thus a reliable spectrum over a bandwidth of 50 MHz was constructed. The expected half-power width of the positronium recombination line is ~ 23.5 MHz (≈ 1436 km s^{-1}) if the temperature of the annihilation region is $\sim 7 \times 10^4$ K (Gehrels et al. 1991).

The phase center of the observation was R.A.(1950) = $17^{\rm h}40^{\rm m}41^{\rm s}.4$ and Decl.(1950) = $-29°43'21''.0$. For calibrating the instrumental gain and frequency responses, the source NRAO 530 (1730−130) was observed for about 5 minutes in each of the half-hour cycles. The flux density scale was set by observing the source 3C 48 (0134+329), whose flux densities at the three observing frequencies were taken to be 5.59 Jy, 5.58 Jy, and 5.56 Jy, respectively. On this scale the observed flux densities of the calibrator NRAO 530 at the three frequencies were found to be 5.78 ± 0.06 Jy, 5.79 ± 0.03 Jy, and 5.79 ± 0.03 Jy, respectively.

The data were processed using the Astronomical Image Processing System (AIPS) developed by the NRAO. After ensuring the consistency of the observations between the two days, one

TABLE 1

PARAMETERS OF THE SOURCES IN FIGURE 1

SOURCE	COORDINATES		FLUX DENSITY (mJy)			
	R.A.(1950)	Decl.(1950)	Peak	Total	EXTENSION	POSITION ANGLE
A	$17^h40^m43^s.03$	$-29°43'25''.8$	0.47 (0.04)	0.47 (0.04)	Unresolved	
B	17 40 42.38	−29 43 04.2	0.27 (0.04)	1.1 (0.05)	$4''.7 \times 2''.6$	$3°.9$
C	17 40 41.86	−29 41 39.0	1.30 (0.04)	6.2 (0.08)	4.2×3.8	167.0
D	17 40 43.55	−29 43 42.2	0.15 (0.04)	2.0 (0.2)		

Numbers in the parentheses are 1 σ errors.

single visibility data base was constructed for both days. Line images were constructed for each of the 16 channels over a 50 MHz band centered around 4911.1056 MHz. A continuum CLEANed image was also constructed. In both cases, an inner cutoff was imposed on the visibilities to filter out most of the confusing structures, close to the Galactic center, larger than 40″.

The continuum image of the field of interest is shown in Figure 1. The parameters of the sources in Figure 1 are given in Table 1. The region around sources A, B, and D is shown in detail in Figure 2. The error cross for 1E 1740.7−2942 from the coded imager TTM on the *MIR* space station (Skinner et al. 1991) is also indicated. No line was detected in the direction of the sources A, B, C, and D to a 3 σ limit of 330 μJy. The spectrum obtained against source A is shown in Figure 3. No continuum has been subtracted from the original spectrum.

3. DISCUSSION

The continuum image in Figure 1 consists of the four features A, B, C, and D. It is clear that source C is extended, outside the error circle of the X-ray source and therefore cannot be associated with 1E 1740.7−2942. Any positronium recombination line with 1E 1740.7−2942 is likely to arise from source A.

3.1. *Upper Limits to the* Ps87α *Recombination Line and its Implications*

We note that the *GRO* observations, during 1991 November 14–27, have not detected any point source of 0.5 MeV annihilation line to a 3 σ upper limit of 3×10^{-4} photons cm^{-2} s^{-1} (W. R. Purcell, private communication). The 3 σ upper limit of 330 μJy to the peak intensity of the Ps87α implies an upper limit to the recombination line photon flux of 2.5×10^{-3} photons cm^{-2} s^{-1}, for an assumed line width of 23.5 MHz.

In the absence of any detailed calculation of the level populations in the excited states of positronium and an understanding of the physical conditions in the region where annihilations take place, there is no simple way of translating the limit on the recombination line flux density to a limit on the annihilation line flux density. On the crude assumption that there will be one recombination line photon per annihilation photon, our upper limit quoted above would be consistent with the limit derived from the *GRO* observations. Such an assumption would mean that almost all the positronium atoms are initially formed in a very high excited state ($n \geq 88$) and each of these atoms will make the transition $n = 88$ to $n = 87$ before annihilating. Clearly such an assumption is optimistic and may overestimate the strength of the recombination line by several

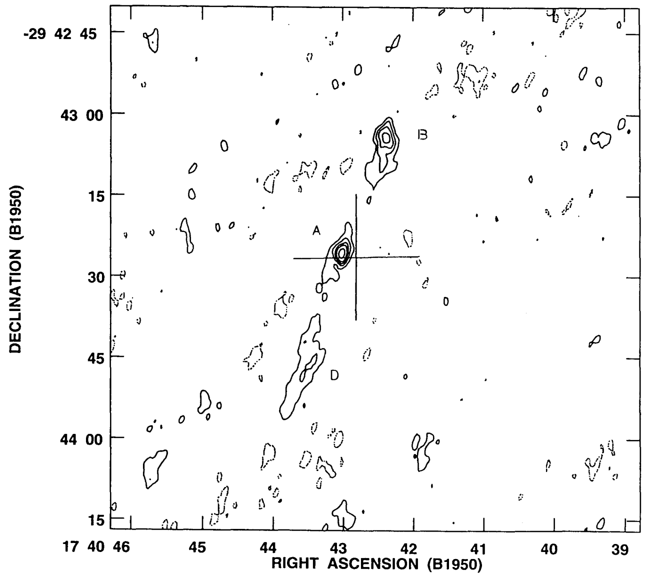

FIG. 2.—A close-up of the field near 1E 1740.7−2942. The contour levels are at −90, 90, 150, 210, 270, 390 μJy beam^{-1}. Error cross is for 1E 1740.7−2942 from the coded imager TTM on *MIR* space station (Skinner et al. 1991). The error circle from *ROSAT* (Phinney 1992) is centered on source A with a diameter of 12″.

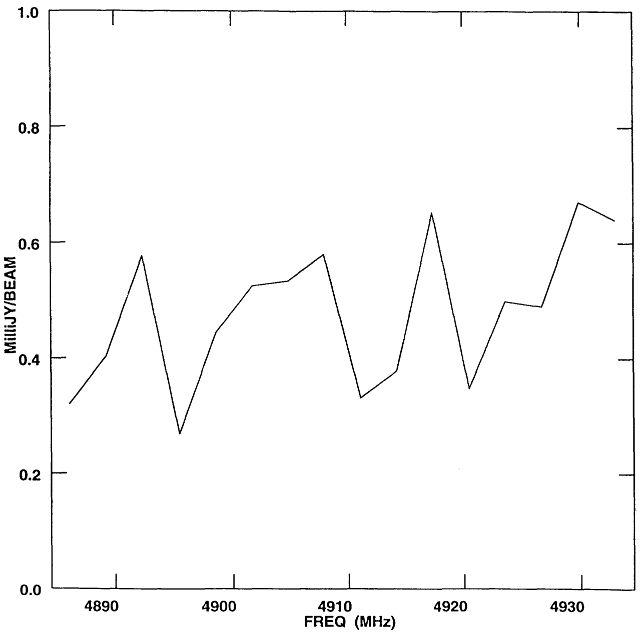

FIG. 3.—Ps87α spectrum toward source A. The rest frequency of the line is 4911.105 MHz. The frequency resolution of the spectrum is 3.125 MHz. The rms noise is 110 μJy beam^{-1}.

orders of magnitude. Some qualitative arguments are outlined below.

There are two processes by which positronium can be formed, namely radiative recombination of positrons and electrons ($e^+ + e^- \rightarrow \text{Ps} + \gamma$) and charge exchange with neutral hydrogen atoms ($e^+ + \text{H} \rightarrow \text{Ps} + \text{H}^+$). Positronium formation and subsequent annihilation have been discussed by several authors (e.g., Crannell et al. 1976; Bussard, Ramaty, & Drachman 1979; Drachman 1983; McClintock 1984; Gould 1989; and Burdyuzha, Kauts, & Yudin 1992). Formation of positronium occurs only at temperatures $\leq 7 \times 10^5$ K. At higher temperatures direct annihilation of positrons and electrons dominate (Gould 1989). In analogy with hydrogen recombination (e.g., Gould 1989; Burdyuzha et al. 1992), the cross section for recombination decreases steeply with increasing quantum number, n. At high energies (i.e., $E_{e+} \gg 6.8$ eV, the ionization energy of positronium), the recombination rate is proportional to $1/n^3$. At lower energies, the rate of change is not as steep but still decreases monotonically with increasing n. It therefore appears that only recombinations of very low energy positrons will contribute to the population of high quantum number states. Furthermore, direct annihilation from a given n state and radiative transitions with $\Delta n > 1$ will significantly decrease the number of recombination line photons. Given that all recombinations will eventually result in the annihilation of positronium, we would then expect that the ratio of the number of (high n) recombination line photons to the number of annihilation photons to be $\ll 1$. In fact, Burdyuzha et al. (1992) estimate that even for $n = 2$, the number of recombination line (i.e., Lα line) photons is only 15% of the number of annihilation line photons. This fraction is likly to decrease steeply with increasing n.

Positronium formation by charge exchange with neutral hydrogen occurs over a narrow range of positron energies from 6.8 eV with the peak at about 16 eV (Drachman 1983). Below 6.8 eV, there is not enough energy to form the lowest energy bound state ($n = 1$) of positronium. At energies above 10.2 and 13.6 eV, excitation of the 2p state of hydrogen and hydrogen ionization dominate (Bussard et al. 1979). The following qualitative arguments show that the process of charge exchange is likely to produce only a small number of positronium atoms in excited states. The first excited state of positronium ($n = 2$) requires an energy of 5.1 eV and therefore this state can be formed only if the initial energy of the positrons exceeds 11.9 eV (i.e., 6.8 + 5.1 eV). Even so, when the energy exceeds 11.9 eV, the cross section for forming the $n = 2$ state of positronium must be much less than the cross section for forming the ground state and carrying the excess energy as kinetic energy of one of the products (Ps or H$^+$), since the phase space available for the latter process is much larger. Similarly, to produce a given excited state of positronium (say, $n = 88$), the initial energy of the positrons must exceed the sum of 6.8 eV and the energy of the excited state. Only a small fraction of these positrons will in fact produce the required excited state and the remaining ones will produce other lower excited states with the excess energy being carried away as the kinetic energy of one of the products. It therefore appears that the number of positronium atoms in excited states, formed through charge exchange, must also decrease rapidly with increasing n.

In summary, both radiative recombination and charge exchange seem to produce only a small fraction of positronium in excited states. Therefore the upper limit on the Ps87α intensity is unlikely to give a useful constraint on the number of annihilation line photons. It appears that unless there is a process by which the excited states of positronium can be highly overpopulated or sources of annihilation radiation greatly exceeding the intensity observed in 1E 1740.7−2942 or the Galactic center region are discovered, the prospects for observing the radio recombination lines of positronium are indeed bleak.

3.2. *Continuum Sources A, B, and D and their Possible Association with 1E 1740.7−2942*

The position of source A falls within the 90% error circle of the position of the X-ray source 1E 1740.7−2942 (Skinner et al. 1991). However, the morphology of the three features A, B, and D, taken together, suggests that they may form a single entity. The structure seen in Figure 2 confirms the report by Mirabel et al. (1992b) that source A is located at the center of an aligned double radio jet. Although the image does not delineate the jets in any detail, the extensions seen in sources A and B, which point at each other, are good indicators of the presence of jet or bridgelike features. We shall therefore consider the features A, B, and D to represent a single radio source consisting of at least three components. The relation between this radio source and the X-ray source 1E 1740.7−2942 can be one of the following.

1. The radio source and the X-ray source are both Galactic objects and associated with each other. The X-ray and radio properties of this source make it an unique object in the Galaxy. The only other Galactic source which may have some similarity with the radio morphology of this object is SS 433 (Margon 1984). However, the dramatic variations in the radio flux density of the core of SS 433, changes in the morphology of its extended features on the time scale of days, and the precession of the jet and various other unique features of SS 433 are apparently absent in this radio source. For these reasons an analogy with SS 433 is not favorable. On the other hand, the X-ray properties of 1E 1740.7−2942 are quite similar to those of Cyg X-1, a well-known black hole candidate in the Galaxy. The normal state X-ray spectrum of 1E 1740.7−2942 and its luminosity in the 4–300 keV band are very similar to those of Cyg X-1 (Sunyaev et al. 1991a, b). But, in the case of Cyg X-1 the radio and X-ray flux variability are anticorrelated. The radio spectral index is flat or even positive (in the sense $S \propto \nu^\alpha$). These and other properties displayed by Cyg X-1 (Hjellming 1973; Hjellming, Gibson, & Owen 1975; Braes & Miley 1976) are not observed in 1E 1740.7−2942. But, on the other hand, Cyg X-1 and SS 433 are themselves very different from each other in their detailed properties although the underlying cause may be the same (Hjellming 1988). It is possible that 1E 1740.7−2942 is yet another unique Galactic object in this class. In this case one might expect changes in the structure and intensity of the sources B and D on a time scale of a few years.

2. The X-ray source is a unique Galactic object and the radio source is a background radio galaxy with a chance positional coincidence. This possibilty seems less likely for two reasons: (*a*) from radio source counts at 5 GHz (e.g., Kellermann & Wall 1987), the chance of finding a random background source with a flux density greater than 1 mJy within the TTM error circle (Fig. 2) is less than 1 in 1000. In addition, recently, X-ray observations from *ROSAT* have become available (Phinney 1992). These observations, with comparable angular resolutions to TTM, confirm similar error cirles

TABLE 2

SUMMARY OF FLUX DENSITY MEASUREMENTS OF SOURCES A AND B

	SOURCE A		SOURCE B		
EPOCH	20 cm	6 cm	20 cm	6 cm	REFERENCE
1989 Mar	<1.0	0.4	1.5	0.25	1
1990 Oct	<0.62	...	1.38(0.31)	<0.36	2
1991 Sep	<0.3	<0.1	...	...	3
1991 Oct	0.31(0.06)	0.18(0.04)	...	...	3
1991 Nov	...	0.47(0.04)	...	0.27(0.04)	4
1992 Jan	...	0.33(0.05)	...	...	5
1992 Feb	...	0.30(0.09)	...	...	5
1992 Mar	...	0.27(0.06)	...	...	5

All flux densities are in mJy. Numbers in the parentheses are 1 σ errors.

REFERENCES.—(1) Prince & Skinner 1991; (2) Gray et al. 1992; (3) Mirabel et al. 1991b; (4) present observations; (5) Mirabel et al. 1992b.

around source A. (*b*) The radio and X-ray flux densities of source A appear to be correlated (Mirabel et al. 1992b).

3. The radio source and the X-ray source are both extragalactic and are associated with each other. The radio morphology of the object seen in Figure 2 is similar to a radio galaxy. The central compact source A and the lobes B and D are collinear and B and D are placed symmetrically about A as observed in many such objects. There are indications that the core source A has a relatively flat spectrum ($\alpha > -0.36$, where $S_\nu \propto \nu^\alpha$; Gray et al. 1992), whereas one of the lobes (B), for which measurements are available, has a spectral index $\alpha \approx -1.5$ (Prince & Skinner 1991). This property is observed in many radio galaxies (Miley 1980).

Regarding the X-ray properties of 1E 1740.7−2942, a variety of extragalactic sources, notably Seyfert I galaxies, quasars, and radio galaxies are known to be powerful emitters of X-rays (Gursky & Schwartz 1977; Pounds 1980). The luminosity of these sources in the 2–10 keV band ranges from 10^{42} to several times 10^{45} ergs s^{-1}. Hard X-ray emission, up to several hundred keV, has been observed in a few objects including Centaurus A (Stark 1979; Rothschild et al. 1979; Gehrels et al. 1983; Rothschild et al. 1983). The variability and changes in the X-ray spectral state observed in 1E 1740.7−2942 have also been observed in several extragalactic radio sources (Pounds 1980; Turner et al. 1985; Makino et al. 1989; Morini, Anselmo, & Molteni 1989). If 1E 1740.7−2942 is an extragalactic source, then an estimate of its distance is required to compare its X-ray luminosity with some of the known sources. The annihilation line observed on 1990 October 13–14 does permit the estimation of a distance if the shift of the line feature toward lower energies is assumed to be due to a cosmological redshift. If we assume a redshift of 0.1 based on the observations of Bouchet et al. (1991) and Sunyaev et al. (1991a, b) (although these authors do not assume so), then the distance to 1E 1740.7−2942 is about 300 Mpc ($H_0 = 100$). The measured X-ray flux in the 2–10 keV band (Kawai et al. 1988) implies a luminosity of 3×10^{45} ergs s^{-1} which lies toward the high end of the X-ray luminosity distribution.

Although the discussions presented above make the extragalactic interpretation of 1E 1740.7−2942 possible, there are some difficulties with this interpretation. Since the total radio flux density of the source (consisting of A, B, and D in Fig. 2) is $S_{4911} = 3.6$ mJy, this implies a luminosity at 178 MHz (P_{178}) of $\sim 9 \times 10^{23}$ W Hz^{-1} (for $z = 0.1$; $\alpha = -1$). The value of P_{178} for extragalactic radio sources lies in the range of 10^{23}–10^{27} W Hz^{-1}. Thus in terms of radio luminosity this source lies toward the lower end of the distribution. An additional difficulty is the observed variability of source A. As can be seen from Figure 4 and Table 2, the flux density of source A increased from 0.18 mJy on 1991 October 7 to 0.47 mJy on 1991 November 16—an increase by a factor of 2.6 in about 40 days. Although the flux densities of the cores of extragalactic radio sources are known to change with time (Kellermann & Owen 1988), variations of this magnitude are not observed on this time scale. If 1E 1740.7−2942 is an extragalactic source, the dramatic annihilation line seen on 1990 October 13–14, should also be observed in many other extragalactic sources. The observations so far have not detected any line (Marsher et al. 1983; Gehrels et al. 1983; Baity et al. 1981, 1984), although the failure to detect the line can be attributed to the highly time variable nature and short duration of the burst as observed in 1E 1740.7−2942.

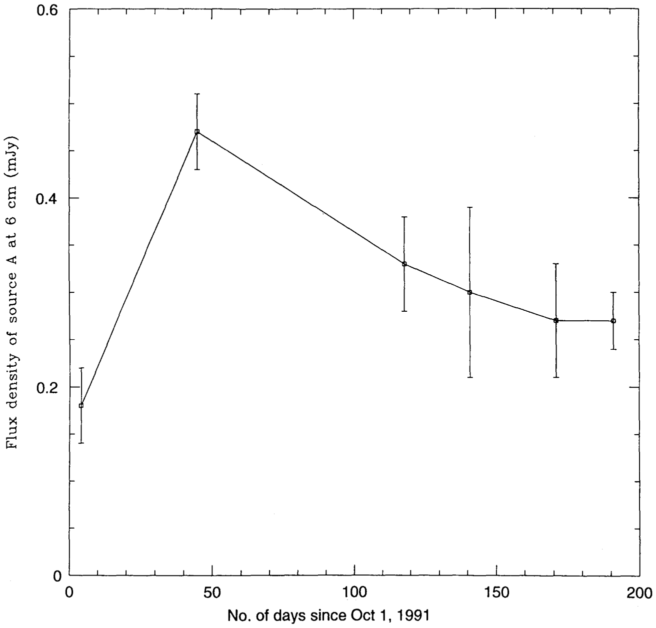

FIG. 4.—Flux density variation of source A at 6 cm. The data are taken from Table 2 and from Mirabel et al. (1992b). Note the rapid increase in the flux density by a factor of 2.6 in 40 days. Our observations correspond to the data point with a flux density of 0.47 mJy.

4. SUMMARY

We have used the Very Large Array to search for a possible Ps87α radio recombination line of positronium from the hard X-ray source 1E 1740.7−2942 from which strong time-variable annihilation radiation was observed by the *GRANAT* satellite in 1990. No line was detected and the 3 σ upper limit to the line strength is 330 μJy for a line width of 23.5 MHz which is expected if the temperature of the annihilation region is 7×10^4 K. This corresponds to an upper limit to the recombination line photon flux of 2.5×10^{-3} photons cm^{-2} s^{-1}. We have presented qualitative arguments to show that both radiative recombination and charge exchange with neutral hydrogen will produce only a small fraction of positronium atoms in highly excited states which in turn can produce radio recombination lines. As such, the above limit, although very sensitive, does not translate to an interesting upper limit on the flux of annihilation photons.

A by-product of the above search is a 6 cm radio continuum image of the field containing the hard X-ray source 1E 1740.7−2942. This image shows a weak radio source with a core and lobe structure, similar to extragalactic double radio sources, with the core lying within the positional error circle (90% confidence) of the X-ray source. Comparison with observations by Mirabel et al. (1992a, b) shows that the radio flux density of the core at 6 cm had increased by a factor of $\approx$2.6 between 1991 October 7 and November 16, and has been decreasing steadily since then. We have considered three possibilities for the relationship between the X-ray and the radio source: (1) both are unique Galactic objects and associated with each other, (2) the X-ray source is a unique Galactic object and the radio source is a background radio galaxy with a chance positional coincidence, and (3) both are extragalactic objects and associated with each other. We find that the second possibility is unlikely and that it is not possible to rule out either the first or the third possibility on the basis of the available evidence. If this object is Galactic, then it must be possible to detect changes in the structure and intensity of the radio lobes on a time scale of a few years. On the other hand, if the source 1E 1740.7−2942 is extragalactic, then continuous monitoring of other similar extragalactic radio sources may reveal transient bursts of the broad annihilation-line radiation.

Note added in manuscript.—Since the submission of this paper we have observed the sources A, B, and D with the VLA in the A-configuration at 20 cm (beam: $2''.7 \times 1''.6$, PA = 7°; rms = 45 μm Jy beam^{-1}). The spectral index of the integrated flux density of source B implied by these observations is $\approx$0.0. The analyses of the 6 and 20 cm observations of Mirabel et al. (1992b) made on 1991 October 3 and 7 are consistent with these values. Source B apparently has a flat spectrum.

The Very Large Array is a part of the National Radio Astronomy Observatory which is operated by the Associated Universities, Inc., under a cooperative agreement with the NSF. We thank D. Bhattacharya, John Biretta, R. D. Ekers, E. B. Fomalont, V. K. Kapahi, and G. Srinivasan for valuable discussions and L. F. Rodriguez, I. F. Mirabel, and W. Purcell for communicating to us their observations prior to publication.

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