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# X-RAY BURST SOURCES NEAR THE GALACTIC CENTER AND THEIR BURST PEAK LUMINOSITIES

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## ABSTRACT

X-ray bursts from the GCX bursters, GX 3+1, Terzan 1, Terzan 5, and MXB 1728−34, all within 0.1 rad from the galactic center, were observed with the *Hakucho* burst monitor system. Distinctly high concentration of burst sources to the galactic center direction and the frequent association of burst sources with globular clusters imply that those burst sources we observed are located spatially near the galactic center. For the probable source distances of ~ 10 kpc, the burst peak luminosities for these sources are found to exceed the Eddington limit for a ~ 1.4 $M_\odot$ neutron star by large factors.

*Subject headings:* stars: luminosities — stars: neutron — X-rays: bursts

## I. INTRODUCTION

It has been noted that identified burst sources were dense near the direction of the galactic center (GC). Recent addition of four new burst sources in the galactic bulge region, GX 3+1, Terzan 1, Terzan 5, and XB 1715−321, discovered from the *Hakucho* observations (Oda *et al.* 1980; Makishima *et al.* 1981*a*, *b*), makes a more convincing case of the conclusion that the celestial distribution of burst sources is steeply peaked toward the GC.

Those burst sources clustering in the direction of the GC are believed to be located spatially near the GC, not only because this is what their sky distribution suggests, but also for the reasons discussed in § III.

We shall report in this *Letter* the results of the *Hakucho* observations of the bursts from GX 3+1, the GC bursters, Terzan 1, Terzan 5, and MXB 1728−34, all within 0.1 rad of the GC. The burst peak luminosities from these sources are found to invariably exceed the Eddington limit for a ~ 1.4 $M_\odot$ neutron star by large factors.

## II. OBSERVATIONAL RESULT FOR THE BURST SOURCES NEAR THE GALACTIC CENTER

We conducted a series of observations of burst sources near the GC with the *Hakucho* burst monitor system (Inoue *et al.* 1979; Kondo *et al.* 1981) from 1980 July 15 through 1980 September 26. From these observations, we discovered GX 3+1 to be burst-active (Oda *et al.* 1980) and also two new burst sources associated with globular clusters Terzan 1 and Terzan 5 (Makishima *et al.* 1981*a*). Many bursts from the GCX bursters and MXB 1728−34 were also observed in the same period. The GCX bursters appear to comprise three burst sources (Lewin *et al.* 1976). We have not yet determined which of the three was or were burst-active, however, and tentatively consider them as one source.

First, the peak energy fluxes of individual bursts are evaluated. Bolometric corrections are applied on the assumption of a blackbody spectrum for the emission of bursts. The apparent blackbody temperature can be determined from the observed hardness ratio, the ratio of the count rates in two energy ranges, 9–22 keV and 1–9 keV, employed in the present observations. These evaluations are subject to the effect of interstellar absorption. The hydrogen column density $N_H$ is taken to be $10^{23}$ cm$^{-2}$ for the GCX burster, as determined for the persistent source 3U 1743−29 (Jones 1977), and $3 \times 10^{22}$ cm$^{-2}$ for MXB 1728−34 (Hoffman, Lewin, and Doty 1977) and GX 3+1 (Jones 1977). The effect of interstellar absorption is found to be unimportant for $N_H \lesssim 3 \times 10^{22}$ cm$^{-2}$. For Terzan 1 and 5, we assume $N_H$ to be $3 \times 10^{22}$ cm$^{-2}$. If this is an underestimate, the

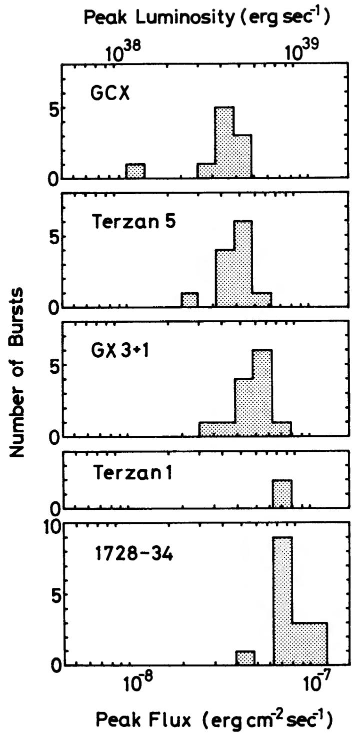


FIG. 1.—Peak energy flux distributions of individual bursts for five burst sources. The upper scale represents the absolute luminosity scale for 10 kpc distance.

energy flux is also underestimated, which does not affect the later discussion. We estimate the obtained energy flux to be correct within 20% for possible systematic errors. The peak energy flux distributions for the five burst sources are shown in Figure 1. The burst peak flux for each source scatters by a factor of 3 or more. The maximum values of the observed burst peak flux for the individual sources are listed in Table 1.

On the assumption of the blackbody emission for bursts, the blackbody radius can be estimated from the observed luminosity and the blackbody temperature. Characteristic of the type I bursts (e.g., van Paradijs 1978), the blackbody radius is found to remain constant through the burst decay. Furthermore, the radius values for different bursts from a source appear to be the same within statistical uncertainties independent of the burst peak luminosity and the burst size. This feature was already reported for MXB 1636−53 (Ohashi *et al.* 1981). The estimated blackbody radii for the distance of 10 kpc for the five individual sources are also given in Table 1.

## III. DISCUSSION

### *a) Distribution of the Burst Sources near the Galactic Center*

The distribution of the burst sources near the GC is shown in the galactic coordinates in Figure 2. Among the total of nearly 30 burst sources known at present, 14 are concentrated within 10° from the GC. These sources are believed to be located spatially near the GC because of the following considerations.

#### i) *Distinct Concentration Centered in the Galactic Center Direction*

The sky density of burst sources near the GC direction is roughly 100 times greater than the average over the celestial sphere. The center of gravity of the 14 burst-source positions is only 1° off the GC. Such a singular concentration other than at the GC seems quite unlikely.

If this cluster of burst sources were not near the GC but located much closer to us, one would expect to find more background sources showing significantly smaller burst peak flux. As a matter of fact, the burst peak fluxes from the sources near the GC direction are typically the Crab Nebula intensity or greater, far above our detection threshold, and few fainter burst sources have been observed.

#### ii) *Association with Globular Clusters*

Eight burst sources out of fourteen within 10° from the GC lie in globular clusters. This number includes a

TABLE 1

MAXIMUM VALUES OF THE OBSERVED BURST PEAK FLUX

| Burst Source | Max. Peak Flux ($10^{-8}$ ergs cm$^{-2}$ s$^{-1}$) | Max. Peak Luminosity[a] ($10^{38}$ ergs s$^{-1}$) | $L^b/L_E$ | Blackbody Radius[a] (km) |
|---|---|---|---|---|
| GCX burster...... | 4.8 ± 1.0 | 5.8 | 2.8 | 7.3 ± 1.1 |
| GX 3+1........... | 6.5 ± 0.5 | 7.8 | 3.7 | 10.7 ± 1.1 |
| Terzan 1........... | 7.4 ± 1.0 | 8.9 | 4.2 | 9.7 ± 1.2 |
| Terzan 5........... | 6.1 ± 0.7 | 7.4 | 3.5 | 9.5 ± 1.2 |
| MXB 1728−34 ... | 11.0 ± 1.6 | 13.2 | 6.3 | 10.1 ± 1.0 |

[a]Estimated for 10 kpc distance and averaged for several bursts. Errors for the radii are 90% confidence limits.
[b]Ratio of the maximum peak luminosity to the Eddington limit for 1.4 $M_{\odot}$ assuming cosmical element abundances ($X = 0.7$), $2.1 \times 10^{38}$ ergs s$^{-1}$.

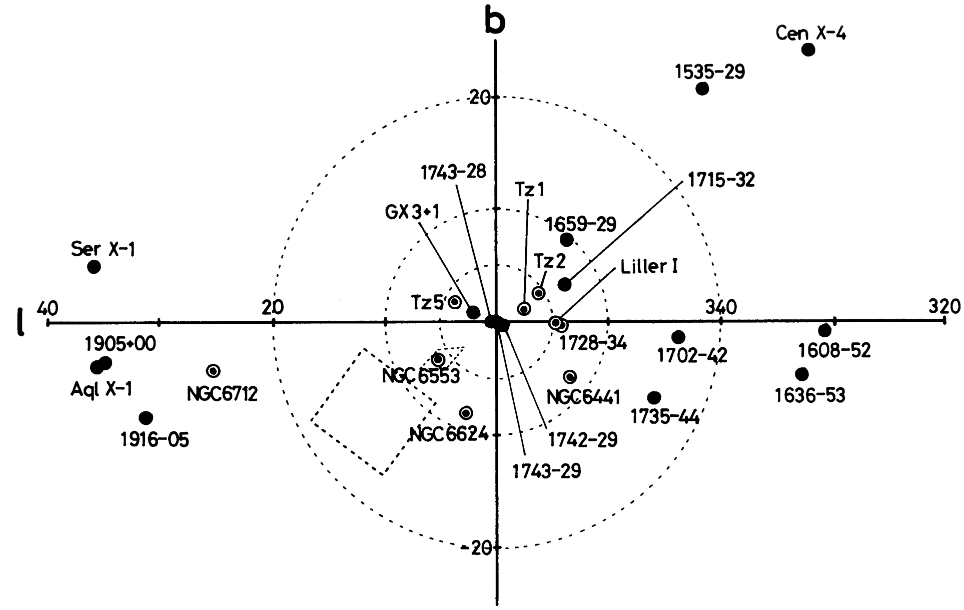


FIG. 2.—Distribution of burst sources plotted in the galactic coordinates; those known to be associated with globular clusters (⊙) and others (●). Dotted circles are 5°, 10°, and 20° from the galactic center.

new globular cluster associated with MXB 1728−34 recently discovered by Grindlay and Hertz (1981), and NGC 6553 which is within the error box of ~ 2 $\deg^2$ for an *OSO 8* burst source (Swank *et al.* 1976). Only two other burst sources are known to be associated with globular clusters. At present, roughly one globular cluster out of ten includes a burst source. Since globular clusters are strongly concentrated toward the GC, such a high density of the globular-cluster burst sources could only be present around the GC.

The optical estimates of the distance also support these sources being near the GC. The estimated distances to NGC 6624 and NGC 6441 are 8.3 kpc (Liller and Carney 1978) and 9.3 kpc (Illingworth and Illingworth 1976), respectively. The distances to Terzan 2 has been estimated at 7 kpc (Grindlay 1978) or 14 kpc (Malkan, Kleinmann, and Apt 1980)

Comparison of the spatial distribution of burst sources with that of globular clusters is an important issue. The spatial distribution of globular clusters is approximately given by $R^{-3.0}$ for the galactocentric distance $R$ in the range 1–10 kpc (Harris 1976; Oort 1977). Oort (1977) estimated the spatial distribution of globular clusters closer to the GC and computed the expected celestial distribution. His result of the estimated numbers of globular clusters in 0–5°, 5°–10°, and 10°–20° from the GC are compared in Table 2 with the observed numbers of globular clusters, burst sources, and those known to be associated with globular clusters.

The observed number of globular clusters is less than that estimated, with increasing difference toward the GC. As it appears from the table, the sky distribution of burst sources is similar to that of globular clusters estimated by Oort for the dispersion velocity of 147 km $s^{-1}$, though not inconsistent with that observed. Because of the poor statistics of burst sources, quantitative comparison remains inconclusive at present. It is also plausible that a considerable number of globular clusters is yet undiscovered in the highly obscured region near the GC. Like the case of MXB 1728−34, more globular clusters may be found in the future in connection with burst sources.

### *b) Burst Peak Luminosities*

From the above discussion, we may conclude that the group of burst sources is located near the GC. If we take the distance to the GC to be 10 kpc, the sources within 0.1 rad of the GC, as well as those we observed, mostly lie between 9 kpc and 11 kpc from us. For a spatial distribution function similar to that of globular clusters, the foreground burst source contribution is estimated to be $\lesssim$ 10%.

Having "known" the distances to be 10 ± 1 kpc, the absolute peak luminosities for the five burst sources observed can be estimated to within about ±20% uncertainties. The absolute luminosity scales so derived are indicated in Figure 1. As a result, almost all the bursts show peak luminosities largely exceeding the Eddington limit of a currently assumed 1.4 $M_{\odot}$ neutron star, $2.1 \times 10^{38}$ ergs $s^{-1}$, for an envelope with cosmical element abundances ($X \approx 0.7$). The maximum values of the observed burst peak luminosities and the ratios to this Eddington limit ($L/L_E$) are given in Table 1.

TABLE 2

DISTRIBUTION OF GLOBULAR CLUSTERS NEAR THE GALACTIC CENTER

| | | | |
|---|---|---|---|
| Angle from the galactic center | 0–5° | 5°–10° | 10°–20° |
| Globular clusters | | | |
| Estimated[a] | 41–101[b] | 41 | 36 |
| Observed[c] | 10 | 20 | 23 |
| Burst sources | | | |
| All | 7 | 7 | 3 |
| Associated with globular clusters | 3 | 5 | 0 |

[a] Oort 1977.

[b] Estimated for two probable dispersion velocities, 134 km s$^{-1}$ and 147 km s$^{-1}$, the smaller number corresponding to the higher velocity.

[c] Harris and Racine 1979.

There have been indications that the burst peak luminosities exceed the above Eddington limit. The average peak flux of the bursts from NGC 6624 observed from *SAS 3* in 1976 March was $1.1 \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$ (Clark *et al.* 1976). At a distance of 8.3 kpc (Liller and Carney 1978), this value implies a peak luminosity of $9 \times 10^{38}$ ergs s$^{-1}$. A burst form Terzan 2 observed by Grindlay *et al.* (1980) from the *Einstein* Observatory had a peak flux of $\sim 6 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$, corresponding to a peak luminosity of $\sim 7 \times 10^{-38}$ ergs s$^{-1}$ for 10 kpc distance. For MXB 1728−34, Hoffman, Lewin, and Doty (1977) reported peak flux of $1.7 \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$ for several bursts. This yields a peak luminosity as large as $2 \times 10^{39}$ ergs s$^{-1}$, which is nearly 10 times greater than the Eddington limit of 1.4 $M_\odot$.

If the radiation of a burst is emitted from the surface of a neutron star, the gravitational effect is important. The ratio of the local luminosity $L_0$ to the local Eddington limit $L_{E,0}$ at the stellar surface is even larger by a factor of $g^{-1}$ than the ratio $L/L_E$ given in Table 1 without considering the gravitational effect, where $g = [1 - (2GM/c^2 r_0)]^{1/2}$ is the gravitational redshift factor for the mass $M$ and the true radius $r_0$. For a model neutron star of $M = 1.4\ M_\odot$ and $r_0 = 7$ km, $g^{-1}$ is approximately 1.6.

Therefore, there seems little doubt that the burst peak luminosities can exceed the Eddington limit for a 1.4 $M_\odot$ neutron star by large factors. Even if an extreme case of a pure helium envelope is considered, this conclusion remains valid.

The apparent supercritical luminosity of bursts does not seem to accompany the dynamical phenomenon in which the radiation pressure blows out the envelope, since the burst rise is much slower than the dynamical time scale on the neutron star surface. The observed result that the blackbody radius remains essentially constant throughout the burst evolution is also against the dynamical picture. As a matter of fact, based on the thermonuclear flash model for bursts, the nuclear energy liberated is only a small fraction of the gravitational potential of the fuel mass.

The estimated blackbody radii for the five burst sources of 10 kpc distance (Table 1) are about the same within a factor of 1.5. This fact would imply that the compact objects involved are mutually similar in size. For a given "apparent" radius $r$ (measured at infinity), there exists an upper limit of the stellar mass $M$ due to the gravitational effect; $M \leq (c^2 r/3\surd(3)G) \approx (r/7.7\ \text{km}) M_\odot$ (van Paradijs 1979). The radius values given in Table 1 are not inconsistent with $r = 11$ km, for which the mass upper limit equals 1.4 $M_\odot$. This does not favor an object more massive than 1.4 $M_\odot$, hence giving a larger Eddington limit. However, it needs to be examined before concluding that the blackbody radius is the actual one, since the apparent blackbody temperature could differ from the effective temperature of radiation.

An entirely different approach to the problem of the apparent supercritical luminosity is to consider if the opacity in the neutron star atmosphere is practically reduced from that given by the Thomson cross section. Several possibilities along this line of thought will be discussed separately.

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