Observational Limits on X-ray Bursts from RRAT J1911+00

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ABSTRACT

The high radio-flux brightness temperature of the recently discovered class of sources known as Rotating RAdio Transients (RRATs) motivates detailed study in the X-ray band. The source RRAT J1911+00 has a (large) error region which includes the frequently observed low-mass X-ray binary transient Aql X-1. We describe analyses of historical X-ray data, searching for X-ray phenomena (sources, behaviors), finding no sources or behaviors which may unequivocally be associated with RRAT J1911+00. We put forward a candidate X-ray counterpart to RRAT J1911+00, discovered in a Chandra observation in Feb 2001, which fades by a factor > 5 prior to April 2004. Archival ROSAT observations detect the source as early as Oct 1992, with a flux comparable to the Feb 2001 Chandra detection. The X-ray flux and optical ($F_X/F_R > 12$) and near infra-red ($F_X/F_J > 35$) limits, as well as the X-ray flux itself, are consistent with an AGN origin, unrelated to RRAT J1911+00. Searches for msec X-ray bursts found no evidence for such a signal, and we place the first observational upper-limit on the X-ray to radio flux ratio of RRAT bursts: $F_X/F_{1.4\,\text{GHz}} < 6 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ mJy$^{-1}$. The upper-limit on the X-ray burst flux (corresponding to $< 2.2 \times 10^{37}(d/3.3$ kpc)$^2$ erg s$^{-1}$, 2-10 keV) requires a limit on the spectral energy density power-law slope of $\alpha < -0.3$ between the radio and X-ray bands. We place a limit on the time-average X-ray burst luminosity, associated with radio bursts, of $\leq 3.4 \times 10^{30} (d/3.3$ kpc)$^2$ erg s$^{-1}$. Future definitive association between CXOU J191121.3+003844 and RRAT J1911+00 could be made with a better radio localization of RRAT J1911+00; or discovery of msec

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X-ray bursts associated with the radio bursts. Adaptive optic infra-red observations of the crowded source field of CXOU J191121.3+003844 will be required to find a NIR counterpart, which may reveal its source class.

Subject headings: stars: flare; stars: neutron; X-rays: stars; pulsars: individual (J1911+00)

1. Introduction

Recently, a new observational class of neutron stars has been proposed (McLaughlin et al. 2006), comprising eleven sources defined by the phenomenon of fast (2-30 ms) radio bursts, which repeat on timescales of 4min - 3hr. Through period folding, periodicities were claimed to be found in the range of $P = 0.4-7$ s for ten of the eleven sources, which suggested association with rotating neutron stars. In three of the eleven sources, period derivatives were claimed, with one suggesting a magnetic field strength of $5 \times 10^{13}$ G – a possible magnetar. Because the $P - \dot{P}$ analysis remains unpublished and undescribed, we regard association of the radio-bursting population with neutron stars to be an unsupported hypothesis; nonetheless, we adopt the hypothesis and nomenclature of referring to the sources as Rotating RAdio Transients (RRATs), and consider their association with neutron stars to be the leading hypothesis.

The proposed class was recently made more intriguing by the discovery of transient pulsed radio emission from a known magnetar, XTE J1810-197 (Camilo et al. 2006), with peak flux density $> 1$ Jy and $89 \pm 5\%$ polarization at 8.4 GHz, with period $P \approx 5.54$ s. The radio pulsation was not present prior to the 2003 discovery outburst of this magnetar (Ibrahim et al. 2004), detected serendipitously from X-ray pulsations during observations of a nearby source; sensitive X-ray observations found a fading two-temperature X-ray source, with luminosity $\approx 10^{34-35}$ erg s$^{-1}$ on timescales of 300 and 900 days (for two different temperature components; Gotthelf & Halpern 2005). Moreover, day-to-day fluctuations in the radio peak flux were observed, of $\approx 2$. This is interpreted to imply the appearance of the radio pulsations is associated with the reconfiguration of the magnetar magnetic field, which takes place associated with magnetar bursting activity (Woods et al. 2001). The relationship between the observed process and RRATs is unclear, however observation of radio and X-ray activity associated with transient magnetic field reconfiguration may be applicable to the RRATs, in light of the observed transient nature of their radio emission.

An X-ray counterpart has been reported for RRAT J1819-1458, discovered serendipitously as CXOU J181934.1−145804 (Reynolds et al. 2006). This X-ray source was observed
with absorption corrected flux $2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.5-8 keV, with an order of magnitude uncertainty due to uncertainty in the absorption) detected within the $5'' \times 32''$ error ellipse of the RRAT. Comparison with the source density of such X-ray sources find the probability of finding such a bright source by chance $<10^{-4}$, compared with the ASCA Galactic Plane Survey (Sugizaki et al. 2001), at the best-fit unabsorbed flux of $2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The X-ray spectrum is soft ($kT=120\pm40$ eV), which supports classification of a thermal, cooling isolated neutron star (INS) – further supported by the absence of a positionally coincident optical or infrared counterpart. The most convincing evidence for association CXOU J181934.1–145804 with RRAT J1819-1458 is the low probability of finding such a bright X-ray source in the RRAT positional error circle. As Reynolds et al. point out, the observed soft spectrum in light of the high Galactic column density ($N_H=1.6 \times 10^{22}$ cm$^{-2}$) in the direction of this source strongly supports interpretation of the X-ray source as within the Galaxy, further supporting a neutron star interpretation. 

A second source, RRAT J1911+00, has an error ellipse of $15' \times 7'(1\sigma)$, which includes the prolific transient neutron star low-mass X-ray binary Aql X-1 (Liu et al. 2001). The derived dispersion measure distance (McLaughlin et al. 2006) is $d=3.3$ kpc, modestly but perhaps not significantly closer than the typical 4-6 kpc distance adopted for Aql X-1. Four radio bursts at $\nu=1.4$ GHz, of half-width $w_{50}=2$ msec were observed in 13 hours of observing – the least active of the tabulated RRATs – with peak fluxes of $S_\nu=250$ mJy. If we take $w_{50}$ to be the light crossing time of the emission region, this implies a source brightness temperature (e.g., Güdel 2002):

$$T_b = 4 \times 10^{22} \left( \frac{S_\nu}{250 \text{ mJy}} \right) \left( \frac{1.4 \text{ GHz}}{\nu} \right)^2 \left( \frac{2 \text{ ms}}{w_{50}} \right)^2 \left( \frac{d}{3.3 \text{ kpc}} \right)^2 \text{ K}$$  \hspace{1cm} (1)

This is significantly above the brightness temperature limit for inverse Compton scattering ($T_B \sim 10^{12} K$) which likely requires a coherent emission mechanism (for this, and other RRATs), possibly accompanied by X-ray emission. The historical X-ray coverage of Aql X-1 permits study of this field (although not covering the entire error box of the RRAT).

In this paper, we report X-ray studies of the field of RRAT J1911+00. We describe a candidate X-ray counterpart (CXOU J191121.3+003844) to the RRAT J1911+00, detected serendipitously in an historical Chandra observation of Aql X-1 (§ 2). In § 4, we describe a search for msec X-ray bursts from the RRAT, deriving the first limit on the X-ray to radio flux ratio for the RRAT bursts. In § 5 we summarize and discuss our results.
2. Observations and Analysis

For analyses, we used CIAO v3.3\(^1\), FTOOLS\(^2\) (Blackburn 1995), and XSPEC v11.3.1 (Arnaud 1996), with common tasks as described. We found existing observations from Chandra, XMM, ROSAT, SWIFT, RXTE, and BeppoSAX in the public archive at HEASARC\(^3\) (Table 1). While there were 11 Chandra ACIS-S imaging observations in the archive, we tabulate only the one observation in which a second X-ray source (that is, other than Aql X-1) was found, as described in the following section.

2.1. Chandra Observation

We used the CIAO tool celldetect with event level=1 and event level=2 observational data to search for sources in the 11 existing ACIS-S Chandra observations, taken between Nov 2000 and Sept 2002. The 1/2′ × 4′ FOV of these observations rotates on the sky so that, except for an area ∼ 1/2′ × 1/2′ near Aql X-1, the observations cover different areas of the sky. The event level=1 data was used for the source search, in addition to the processed event level=2 data, since msec duration X-ray bursting activity could result in pile-up; events associated with a candidate RRAT counterpart may be flagged as cosmic ray events and filtered from the observation data. With a signal-to-noise limit of > 4, we found no sources which appeared in level=1 and not level=2 data in any of 11 Chandra/ACIS-S imaging observations. We also found two sources which appeared in both the level=1 and level=2 data, one of which is Aql X-1. The second X-ray source is localized R.A.=19h11m21s.36, dec.=00d38m43.69s (J2000) ±0.6″ (90% confidence), approximately 3.9′ from Aql X-1. The position of this object was not within the FOV of any of the other 10 existing Chandra observations. No USNO-B1.0 or 2MASS source is cataloged within 1″ of this position. We designate the unidentified X-ray source as CXOU J191121.3+003844, and performed a more detailed analysis to search for RRAT or neutron-star type properties.

\(^1\)http://cxc.harvard.edu/ciao/  
\(^2\)http://heasarc.gsfc.nasa.gov/ftools/  
\(^3\)http://heasarc.gsfc.nasa.gov/
2.1.1. CXOU J191121.3+003844

We extracted data within 4'' of CXOU J191121.3+003844, finding 100 counts in the source region; we neglect background counts (∼3 counts) throughout the analysis.

Spectral Analysis. We performed spectral analysis, extracting a spectrum of CXOU J191121.3+003844 from the event level=2 data, using data in the 0.5-10 keV range, and grouping PI bins to have between 18 and 21 counts and an energy width greater than the energy resolution at the average photon energy. A systematic uncertainty of 4% was applied to the spectrum and the absorption was held fixed at \( N_H = 3.3 \times 10^{21} \text{ cm}^{-2} \) (Dickey & Lockman 1990). Results are shown in Table 2. An absorbed blackbody model does not produce an acceptable fit (\( \chi^2 = 4.47 \), 3 degrees of freedom, or dof, Prob=4×10^{-3}). A power-law model fits acceptably (\( \chi^2 = 0.65 \), 3 dof, Prob=0.59) with a photon power-law slope \( \alpha = 1.0^{+0.3}_{-0.4} \), and an unabsorbed flux of \( 1.8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \) (0.5-8 keV), for a luminosity of \( 2.4 \times 10^{32} \left( D/3.3 \text{ kpc} \right)^2 \text{ erg s}^{-1} \).

Pulsation Search. To search for pulsations, we produced a power density spectrum (PDS; Press et al. 1995) using FFTW (Frigo & Johnson 1998), with frequency resolution of 0.116 mHz, and a Nyquist frequency of 1.13368 Hz. We find no evidence of coherent pulsations in the 0.0011-1.133 Hz range, with an upper-limit (based on the greatest observed power) of <42% rms. The observation is not very sensitive due to the low number of counts.

Bursting Activity. Due to the ∼0.4 s time resolution of the Chandra data, a ∼msec burst of (multiple) X-rays, such as might accompany the observed radio bursts, could result in instrumental pile-up – in which multiple X-ray photons are counted as a single photon, their photo-electrons summed into a single count, which is assigned a commensurately higher photon energy. Such a count could be flagged as a cosmic ray and removed between the level=1 and 2 data processing; or it could be assigned a to high Pulse Invariant (PI) channels in the level=1 data and remain in the level=2 data. To investigate ∼msec bursting activity of CXOU J191121.3+003844, with this data the high PI channels of the event level=1 observation were compared to the background.

In a 4'' region about the source, event level=1 data contained 109 counts, while the event level=2 contained 100 counts, for 9 counts rejected as cosmic rays. In a 33'' region away from the source, event level=1 data contained 860 counts, while event level=2 data contained 247 counts; this corresponds to an average 9±0.3 events rejected between level=1 and level=2 data in our source region – consistent with that observed. We therefore find no evidence of msec X-ray bursts (rejected as cosmic rays) in the source region.

Optical/NIR Flux Ratios. We obtained J-band imaging of CXOU J191121.3+003844 using the Wide-field Infrared Camera (WIRC; Wilson et al. 2003) at prime focus of the Palo-
We took individual exposures of one minute (as $2 \times 30$ s), obtaining 20 dithered exposures in all. Individual frames were dark-subtracted and flat-fielded using afternoon calibrations; a fringe image was created from sky exposures and subtracted from the frames; bad pixels and cosmic rays in individual frames were identified and masked, and the frames registered and combined. Final astrometric and photometric calibration was performed against the 2MASS catalog. Since Aql X-1 is detected in the final WIRC image, we are able to register directly against the Chandra image, localizing CXOU J191121.3+003844 to within $\pm 0.3''$; we find a position for the source of R.A. 19:11:21.41, Dec +00:38:44.5 (J2000). In Fig. 3(a) we present a portion of the WIRC image including the position of CXOU J191121.3+003844. We observe no NIR counterpart to $J > 21.2$ mag.

We then obtained $r'$-band imaging of the field using the Large Format Camera (LFC$^4$) at prime focus of the Hale Telescope on 1 August 2006 UT (mean epoch: 08:34 UT). We obtained $6 \times 120$ s dithered exposures which were then bias-subtracted, flat-fielded, registered against the NOMAD catalog, and combined (with bad pixel and cosmic ray masking). A portion of the resulting image is shown in Fig. 3(b). Although scattered light from nearby stars is visible at the position of CXOU J191121.3+003844, no point-like source is apparent. Photometric registration against the NOMAD catalog (with $R$-band magnitudes from USNO-B1.0) allows us to set a limit of $R > 22.8$ mag on the brightness of any point source.

To calculate X-ray to optical/NIR flux ratios for CXOU J191121.3+003844, it is necessary to correct our observed limits for Galactic extinction. Since the source lies in the plane of the Galaxy, the total Galactic reddening is uncertain; however, the estimate from Schlegel et al. (1998) is $E(B-V) = 0.73$ mag, which implies extinctions of $A_R = 1.95$ mag and $A_J = 0.66$ mag, respectively. Applying these gives extinction-corrected limits of $R > 20.8$ mag and $J > 20.5$ mag for any point-source counterpart to CXOU J191121.3+003844. Constructing the ratio from the source’s observed 2–10 keV X-ray flux to our extinction-corrected limits, we then find $F_X/F_R > 12$ and $F_X/F_J > 35$; these values are inconsistent with those for clusters, stars, and isolated white dwarfs (see, for example, Beuermann et al. 1999; $^5$), but are consistent with QSOs/AGN, CVs and other X-ray binaries.

$^4$http://www.astro.caltech.edu/palomar/200inch/lfc/index.html

$^5$compare with http://heasarc.gsfc.nasa.gov/wgacat/about.html, Figure 13
2.1.2. Aql X-1

As Aql X-1 also fell within the error ellipse of RRAT J1911+00, activity from Aql X-1 that could be associated with a $\sim$ msec radio burst was investigated. There are 11 historical Chandra observations of Aql X-1 taken with ACIS-S. CXOU J191121.3+003844 is only in one of these observations and the coordinates of CXOU J191121.3+003844 do not fall within in the FOV of any of the other 10 Chandra observations. Using these 11 Chandra observations, source counts were extracted from the event level=1 files using a 5$''$ radius extraction region, centered on Aql X-1. Background counts from a circle of 33$''$ far from the source were also extracted from each of the 11 observations. All the counts in each PI channel were summed from each of the observations for the source and the background. Then the PI channels were binned such that 16 channels became one bin. In the highest binned PI channel there are a total of 48 counts from the Aql X-1 regions (source plus background) and 38 background region area corrected counts. Treating the background counts as the mean, the probability of getting 48 counts or more is 7% using the Poisson probability distribution. Thus, no significant counts in the high PI channel are found in excess of that expected from the background.

3. Historical X-ray Flux of CXOU J191121.3+003844

We examined the history of X-ray observations of this source. These are described in Table 1, including the dates of observations, instruments used, the observation duration, the energy-counts ratio (ECR) for converting countrate to flux, and the corresponding flux (or upper limit) for CXOU J191121.3+003844. Below, we give pertinent details for the individual observations, sorted by observatory.

We did not analyse data from RXTE for a flux limit, as we found the observed flux from the candidate counterpart produce a countrate ($\approx$0.01 c/s), well below the detection limit, even for pulsed emission, in $<10^5$ sec; the required integration times are even longer when Aql X-1, which shares the RXTE FOV, is active.

We examined visually but did not analyse in detail four BeppoSAX observations taken during March 8-20 1997, associated with an outburst of Aql X-1. The large point spread function (9.7$'$ FWHM in LECS; 75$''$ half-power radius in MECS) overlapping PSF of Aql X-1 (3.9$'$ away) at the source position precludes source detection at fluxes comparable to that observed in other observations. However, visual inspection of LECS and MECS images shows no evidence for any X-ray source of flux comparable to that of Aql X-1 during any observing epoch.
**ROSAT.** For the PSPC observations, we used a source extraction radius of 15″ about the position of the candidate, and background from an annulus 20″ and 75″ inner- and outer-radius centered at the source position.

**XMM.** CXOU J191121.3+003844 was not detected in either of the two existing XMM observations. Background counts were extracted from an annulus of 20″ and 40″ inner- and outer-radius (respectively) centered on CXOU J191121.3+003844.

**SWIFT.** We used an extraction radius of 30″ about the source position, and background from an annulus of inner- and outer-radius of 40″ and 150″, respectively. Of two observations, separated by 7 days in 2006, no X-ray source is detected at the position of the *Chandra* source.

The resulting X-ray measured X-ray fluxes and flux limits are given in Table 1, and are shown in Fig. 1. The X-ray source was detected as early as Oct 1992, and as recently as Feb 2001. However, 90% confidence limits measured with XMM and SWIFT show the X-ray source has faded since its Feb 2001 detection using *Chandra*; comparison with the results of the 2004 Apr 19 XMM observation show that the source faded by a factor of $\gtrsim 5$.

4. **RXTE/PCA X-ray Burst Search**

We also searched for X-ray bursts in *RXTE*/PCA data while the instrument is pointed at Aql X-1. We examined 25.6 hours of data from 39 observations in the public Archive\(^6\), taken with the Proportional Counter Array (Swank et al. 1996) and data acquired in Event mode $E_{12564M01s}$, $E_{500us64M01s}$, using PHA channels 5-27 only; these correspond, depending on the observational epoch, to photon energy ranges of 1.5-7.4 keV, up to 2.0-11.5 keV. We excluded event channel 0 (corresponding to PHA channels 0-4), as there are frequent burst-like-events in this channel which appear in observations of other objects as well; and which are largely concentrated in the Proportional Counter Units (PCUs) PCU1, PCU3 and PCU4. These events are understood to be due to high-voltage breakdown in these detector units. We selected event channel 16 (PHA channel 27) as the upper energy channel, to minimize background while permitting observational bandwidth over an astrophysically interesting range.

Our search method proceeded as follows: we used data from 3, 4, or 5 PCUs, the number of which depended on how many were in operation during the selected observation. We examined observations in which the average countrate was $\leq 400$ c/s following energy selection, a compromise between burst-flux sensitivity and high integration time. For each

\(^{6}\text{http://legacy.gsfc.nasa.gov}\)
count, we measured the associated average countrate from within ±1 second, producing a 2-second running average countrate.

At the time of each count, we found the number \( N \) all counts within ±1.106 ms, excluding the initial count (that is, there are \( N + 1 \) counts in each period). We calculated the probability \( P_{\text{trigger}} \) of observing \( N \) counts from a non-variable countrate, where we assumed the average countrate is the associated average countrate within ±1 s of the count. When \( P_{\text{trigger}} \times N_{\text{phot}} < 1 \), where \( N_{\text{phot}} \) is the number of counts in the particular individual observation, we made note of the event as a possible trigger to be examined later.

Finally, we filtered out triggers in which counts are found improbably concentrated in a single PCU detector – presumably, due to a detector high-voltage breakdown. When one of the \( N_{\text{PCU}} \) PCUs contains the most counts \( k \), we find the probability \( P \) for \( \geq k \) of \( N \) counts to be found in a single PCU:

\[
P(N, N_{\text{PCU}}, k) = \frac{P_T(N, N_{\text{PCU}}, k)}{P_T(N, N_{\text{PCU}}, 0)}
\]

\[
P_T(N, N_{\text{PCU}}, k) = \sum_{i=k}^{N} B(N, N_{\text{PCU}}, i) \times B_2(N - i, N_{\text{PCU}} - 1, i)
\]

\[
B(N, N_{\text{PCU}}, k) = \frac{N!}{k!(N-k)!} \left( \frac{1}{N_{\text{PCU}}} \right)^k \left( 1 - \frac{1}{N_{\text{PCU}}} \right)^{N-k}
\]

\[
B_2(N, N_{\text{PCU}}, k) = \sum_{i=0}^{k} B(N, N_{\text{PCU}}, i) B_2(N - i, N_{\text{PCU}} - 1, i)
\]

\[
= \begin{cases} 
1 & , N_{\text{PCU}} \neq 1 \\
0 & , N_{\text{PCU}} = 1, k \neq N \end{cases}
\]

Here, \( P_T(N, N_{\text{PCU}}, k) \) is the un-normalized probability of observing \( \geq k \) counts (of \( N \) total counts) in a single PCU, when the \( N \) counts are distributed randomly among the \( N_{\text{PCU}} \) PCUs; \( B(N, N_{\text{PCU}}, k) \) is the binomial probability of observing \( k \) counts (of \( N \) total counts) in one particular PCU (of \( N_{\text{PCU}} \) PCUs); and \( B_2(N, N_{\text{PCU}}, k) \) is the probability of observing no more than \( k \) counts in a particular PCU nor in the remaining \( N_{\text{PCU}} - 1 \) PCUs. When \( P(N, N_{\text{PCU}}, k) \leq 0.01 \), we considered the counts to be improbably concentrated to a single PCU to be a celestial X-ray burst (in which the counts should be distributed evenly among the PCUs, on average), and the trigger was filtered out as likely due to a detector-related effect. We expect only 1% of all celestial X-ray bursts would match this trigger, and so it would negligibly affect our detected burst rate.

In the 25.6 hr of data, we found 6 possible triggers; the most significant of these had a chance probability of being observed from a Poisson fluctuation during the single observation of 4% – consistent with a Poisson fluctuation expected from examining 39 observations. We thus find no evidence of celestial X-ray bursts on a 2 msec timescale in this field.
We place a limit on the burst rate as a function of burst flux which could have passed undetected during these observations. We would have considered a burst to be detected if the number of counts in a burst event would only have been produced across the entire dataset from a background fluctuation in a dataset 100× as large, on average. Since zero bursts met this criteria, we take the 95% confidence upper-limit to the burst rate to be \(2/T(F)\), where \(T(F)\) is the total integrated time as a function of average burst flux \(F\) (there is a 5% probability of observing zero events when 2 are expected). We find the 2-10 keV flux \(F\) from the count rate limits derived from the observation, \(F = (I/(1000c/s/PCU))10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\), where \(I\) is the burst countrate limit (averaged over 2.2msec); we assumed a photon power-law spectral slope of \(\alpha = 1\) and \(N_{\text{H},22}=0.3\).

During 25.6 hr of observation, we place a 90% confidence upper-limit on the flux of any 2msec burst which occurred as \(<1.7\times10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\) (<0.9 mJy in the 2-10 keV region), or \(<2.2\times10^{37}(d/3.3\text{ kpc})^2\) erg s\(^{-1}\). Assuming a flux density in power-law form \(F(\nu) = A\nu^\alpha\) \(\mu\text{Jy}\) and comparing this limit at 2 keV, with the radio detection at 1.4 GHz, we derive an upper-limit of \(\alpha < -0.3\). For a burst rate comparable to that observed from RRAT J1911+00 (0.1 hr\(^{-1}\)), the minimum detectable burst flux is \(\approx 1.5\times10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\), 2-10 keV). If we assume a radio burst rate of 0.08 hr\(^{-1}\) for a radio flux of 250 mJy at 1.4 GHz (comparable to that observed from RRAT J1911+00), then we expect that 2 such bursts, on average, would have gone off during our observations, and the probability that zero such bursts would have gone off is < 5%. We therefore can place an upper-limit on the X-ray/radio flux ratio of the RRAT bursts:

\[
F_X/F_{1.4\text{GHz}} \lesssim 6\times10^{-11}\text{ erg cm}^{-2}\text{ s}^{-1}\text{ mJy}^{-1}
\]

This corresponds to \(F_X/F_{1.4\text{GHz}} \lesssim 10^{15.8}\) Hz. This limit is comparable to the measured \(F_X/F_{1.4\text{GHz}}\) for stellar coronal flares (which are phenomenologically unlike the radio bursts of RRATs, in that their durations are typically \(10^{2-3}\) sec) (Guedel & Benz 1993).

This \(F_X/F_{1.4\text{GHz}}\) upper-limit is significantly above the peak pulsed value for millisecond pulsars (MSPs). For example, PSR B1821-24 has a peak countrate, observed with Chandra/HRC-S, of 62 counts in the 30.54\(\mu\)s peak bin (1% duty cycle) of the 52586 sec observation, (0.117 c/s), for 3.5\times10^{-12}\ erg cm\(^{-2}\) s\(^{-1}\)(2-10 keV), with 13% uncertainty, ignoring spectral uncertainty Rutledge et al. (2004). The peak radio flux (1.4 GHz) is \(\sim 70\) mJy, with 15% uncertainty Cognard et al. (1996); this corresponds to \(F_X/F_{1.4\text{GHz}} = 5\times10^{-14}\text{ erg cm}^{-2}\text{ s}^{-1}\text{ mJy}^{-1}\) — a factor of 1200 below than the limit we set here for RRAT J1911+00.

While magnetars would be a useful source class to compare with this X-ray/radio flux ratio — in particular, the ms bursts observed from anomalous X-ray pulsars (AXPs; Gavriil
et al. 2002; Kaspi et al. 2003; Gavriil et al. 2004; Woods et al. 2005) or those from soft-
gamma-ray repeaters (SGRs; Göğüş et al. 1999; Göğüş et al. 2001) – no published limits on
the X-ray/radio ratio of the msec bursts from magnetars exist.

With a measured limit for the X-ray burst flux of $F_{\text{lim}} < 1.5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (2-
10 keV); burst duration of 2 ms, and an average burst rate of $4/13$ hr$^{-1}$, this implies an
upper-limit to the time-averaged X-ray burst luminosity of $\leq 3.4 \times 10^{30} (d/3.3 \text{ kpc})^2$ erg s$^{-1}$.

5. Discussion and Conclusions

The historical X-ray coverage of the error box of RRAT J1911+00 exists due to the
source’s close proximity to Aql X-1, a transient LMXB. Other than Aql X-1 itself, we find one
unidentified X-ray source in the Chandra observations, which has the following properties:
moderately hard spectrum ($\alpha = 1$ photon power-law index); intensity variability by a factor of
$\gtrsim 5$ over timescales of $\lesssim 5$ yrs. We find no evidence of pulsations, but with weak limits ($\leq 42\%$
rms) in the 0.0011-1.133 Hz range.

The observed X-ray flux gives a value of $F_X/F_R > 12$, and $F_X/F_J > 35$, limits which
are consistent with an AGN, as well as with the much higher such ratios of clusters, CV/low-
mass-X-ray binaries, and isolated neutron stars. Based on the density of AGN, the proba-
ibility of finding one such object in the $15' \times 7'$ error box of RRAT J1911+00 is $\sim 0.3$ (Has-
inger et al. 2001), which is sufficiently large as to permit an explanation for this source as simply
an unrelated AGN in the source field. We thus do not rule out an AGN origin for this X-ray
source. Though we regard the suggestion that RRATs are neutron stars to be the leading
hypothesis, we would not exclude the possibility that one of the radio-bursting sources could
be of a different origin.

Based on the fading X-ray behavior, we put forward CXOU J191121.3+003844 as a
candidate X-ray counterpart to RRAT J1911+00, warranting further study. Both CXOU
J191121.3+003844 and Aql X-1 fall within the error ellipse of RRAT J1911+00. No new
activity was detected from Aql X-1. Observations which would securely identify this object
as the counterpart include a 1" radio localization of RRAT J1911+00, securing positional
coincidence; or detection of fast (\sim ms) X-ray bursts, which would be associated with the
radio-burst phenomena.

The limit we place on the X-ray/radio flux ratio of the RRAT bursts, while the first
such limit for this phenomenon, does not seem to exclude any known transient phenomena;
the limit can be used to plan future, more sensitive searches.
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Fig. 1.— X-ray flux history of CXOU J191121.3+003844. Upper-limits are 90% confidence. These values are also given in Table 1.

Fig. 2.— 95% confidence upper-limit burst rates for 2-10 keV X-ray bursts (2 ms duration) for an on-axis source during 25.6 hrs of RXTE/PCA observations of Aql X-1. The field of view (FOV) has 50% response at 30′, and therefore includes the position of RRAT J1911+00.

Fig. 3.— Optical and near-infrared images of the region of sky surrounding CXOU J191121.3+003844. (a) Near-infrared (J-band) image from our Hale Telescope + WIRC observations. The seeing in this image is 0.9″; no counterpart is identified to $J > 21.2$ mag as calibrated against the 2MASS catalog. (b) Optical ($r'$-band) image from our Hale Telescope + LFC observations. The seeing in this image is 1.3″. No counterpart is identified to $R > 22.8$ mag as calibrated against the USNO-B1.0 catalog. Note that although scattered light from nearby bright stars is visible at the position of CXOU J191121.3+003844, no point-like object is seen. The total Galactic reddening in this direction is uncertain but estimated to be $E(B-V) = 0.73$ mag, yielding extinction estimates of $A_R = 1.95$ mag and $A_J = 0.66$ mag, respectively (Schlegel et al. 1998).
Figure 1

Flux History

CXOU J191121.4+003844

Flux (10^{-13} ergs s^{-1} cm^{-2}, 0.5-10 keV)

Year (fractional)
Figure 2

X-ray Burst Rate Limit

RRAT J1911+00

Burst flux (ergs cm\(^{-2}\) s\(^{-1}\), 2–10 keV)
### Table 1. Observations

| Start Time (UT) | Obs/Instr.          | Duration (sec) | Source Counts \(^a\) | ECR \(^b\)  | Source Flux \(^c\) |
|-----------------|---------------------|----------------|----------------------|------------|-------------------|
| 1991 Mar 24 03:19 | ROSAT/HRI          | 4350           | <5                   | 4.5×10\(^{-10}\) | <5.2             |
| 1992 Oct 15 13:18 | ROSAT/PSPC         | 13861          | 10.5±4               | 1.6×10\(^{-10}\) | (1.2±0.4)        |
| 1993 Mar 24 04:40 | ROSAT/PSPC         | 12088          | 14.4±4               | ⋯          | (1.9±0.4)        |
| 2001 Feb 19 11:25 | Chandra/ACIS-S     | 7787           | 97±10                | 2.0×10\(^{-11}\) | (2.4±0.2)        |
| 2004 Apr 13 18:30 | XMM/EPIC/pn        | 8036           | <64                  | 1.2×10\(^{-11}\) | <1.0             |
| 2004 Apr 19 13:36 | XMM/EPIC/pn        | 21125          | <70                  | 1.2×10\(^{-11}\) | <0.4             |
| 2006 Mar 7 00:19  | SWIFT/XRT          | 2876           | <4                   | 9.7×10\(^{-11}\) | <1.3             |
| 2006 Mar 14 00:58 | SWIFT/XRT          | 2405           | <4                   | ⋯          | <1.6             |

\(^a\)The expected average background number of counts has been subtracted, which can produce measurements of fractional numbers of counts. Upper limits are 90% confidence.

\(^b\)Count rate to flux conversion factor, for unabsorbed flux (erg cm\(^{-2}\)s\(^{-1}\), 0.5-10 keV) per source count/sec, assuming \(N_H=0.33\times10^{22}\) cm\(^{-2}\) and a photon power-law index of \(\alpha=0.9\).

\(^c\)Source Unabsorbed Flux (units of \(10^{-13}\) erg cm\(^{-2}\)s\(^{-1}\), 0.5-10 keV)
Table 2: Spectral fits to CXOU J191121.3+003844

| Model: Absorbed Blackbody |  |
|---------------------------|--|
| $N_{H,22}$ (cm$^{-2}$)    | (0.33) |
| kT (keV)                  | $1.2^{+0.3}_{-0.4}$ |
| $N_{BB}^{a}$              | $1.91^{+1.05}_{-0.69} \times 10^{-6}$ |
| Model flux$^{b}$          | $1.43 \times 10^{-13}$ |
| $\chi^2$/dof(prob)        | 4.47/3(3.83×10$^{-3}$) |

| Model: Absorbed Powerlaw  |  |
|---------------------------|--|
| $N_{H,22}$ (cm$^{-2}$)    | (0.33) |
| $\alpha^{c}$              | $1.0^{+0.3}_{-0.4}$ |
| $N_{PL}^{d}$              | $1.5^{+0.5}_{-0.4} \times 10^{-5}$ |
| Model Flux$^{b}$          | $1.8 \times 10^{-13}$ |
| $\chi^2$/dof(prob)        | 0.646/3(0.585) |

Note. — The spectral parameter fits to the CXOU J191121.3+003844 spectrum extracted from the level=2 event file of Chandra observation 709. The extracted spectrum contained 100 counts and the background was not subtracted. All errors are 90% confidence.

$^{a}$ $L_{39}/D_{10}^2$

$^{b}$ best-fit unabsorbed flux, ergs cm$^{-2}$s$^{-1}$ (0.5-8.0keV)

$^{c}$ power-law index

$^{d}$ photons cm$^{-2}$s$^{-1}$ at 1keV