Chandra Resolves the Double FU Orionis System RNO 1B/1C in X-Rays

Stephen L. Skinner1 and Manuel Güdel2
1 Center for Astrophysics and Space Astronomy (CASA), Univ. of Colorado, Boulder, CO 80309-0389, USA; stephen.skinner@colorado.edu
2 Dept. of Astrophysics, Univ. of Vienna, Türkenschanzstr. 17, A-1180 Vienna, Austria;manuel.guedel@univie.ac.at

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Abstract

We present new Chandra X-ray observations of the close pair of young stars RNO 1B and 1C (6″ separation) located in the L1287 cloud. RNO 1B erupted in 1978–1990 and is classified as an FU Orionis star (FUor). RNO 1C also shows most of the properties of an FUor but no eruption has been seen yet. Only a few dozen FUors are known and the presence of two such objects with a small angular separation is rare, suggesting a common origin. Both stars were faintly detected by Chandra and we summarize their X-ray properties within the framework of other previously detected FUors. We also report other X-ray detections in L1287 including the deeply embedded young star RNO 1G, the jet-like radio source VLA 3, and an enigmatic hard flaring source with no Two Micron All Sky Survey counterpart that was only detected in the second of the two Chandra exposures.

Unified Astronomy Thesaurus concepts: Young stellar objects (1834); FU Orionis stars (553); T Tauri stars (1681)

1. Introduction

FUors are low-mass pre-main-sequence stars that undergo large optical or infrared (IR) outbursts of several magnitudes followed by a slow decay on timescales of decades or longer. The prototype FU Ori erupted optically in 1936–1937 and is still in slow decline. The outbursts are thought to be due to a dramatic increase in the accretion rate from the circumstellar disk onto the star. The enhanced accretion is accompanied by development of a strong cool wind. FUors also show wavelength-dependent spectral types mimicking low surface gravity F–G giants or supergiants in the optical (attributed to a self-luminous accretion disk), infrared excesses, and 2.3 μm CO absorption.

Only about two dozen FUors are known (Audard et al. 2014; Connelley & Reipurth 2018, hereafter CR18). It is thus quite remarkable that a close pair of such objects, RNO 1B and 1C (6″ separation), exists in the L1287 cloud. At the L1287 distance of 929 ± 34 pc (Reid et al. 2014), their separation is ≈5574 au. The two stars probably formed contemporaneously and it has been suggested that both 1B and 1C may be close binaries, comprising a hierarchical quadruple system (Reipurth & Aspin 2004).

The L1287 region contains RNO 1, which was listed in the catalog of red and/or nebulous objects (RNO) compiled by Cohen (1980). Subsequently, Staude & Neckel (1991, hereafter SN91) obtained J-band images which resolved the nebulous RNO 1 region into several compact knots including the close pair RNO 1B and 1C, now known to be young stars (Kenyon et al. 1993). They have similar Two Micron All Sky Survey (2MASS) $K_s$ magnitudes of $K_s = 7.76$ (1B) and $K_s = 7.54$ (1C). Both are viewed through high extinction. Estimates for RNO 1B are $A_V ≈ 9.2$ mag (SN91) to 14.5 ± 1 mag (CR18). RNO 1C is redder with $A_V ≈ 12$ mag (SN91) to 19.5 ± 4 mag (CR18). RNO 1B (=V710 Cas) brightened by at least 3 mag in the $R$ band between 1978–1990 (SN91) and is a classical (outburst) FUor. No eruption has yet been seen in RNO 1C but it does show most of the defining features of the class, so it is classified as FUor-like (CR18; Kenyon et al. 1993).

We report the first X-ray detection of RNO 1B and 1C. Our main objective was to use Chandra’s excellent spatial resolution to resolve the pair and quantify their X-ray properties, placing them into context with other X-ray detected FUors such as FU Ori (Skinner et al. 2006, 2010) and the classical FUor V1735 Cyg (Skinner et al. 2009).

2. Observations

We observed RNO 1B/1C with the Chandra Advanced CCD Imaging Spectrometer (ACIS-I) in two separate exposures on 2018 Mar 20 (Obs ID: 20135; 34.507 ks live time) and 2018 May 29 (Obs ID: 21041; 24.636 ks) providing a total live time of 59.143 ks. The ACIS detector is sensitive in the $E ≈0.4–10$ keV energy range with a pixel size of 0.″492. For on-axis sources, 90% of the encircled energy fraction (EEF) lies within a radius of $R_{90} ≈0.′′9$ at $E = 1$ keV. The EEF is energy dependent and $R_{90}$ increases toward higher energies.3

Data were reduced using standard threads in the Chandra Interactive Analysis of Observations (CIAO v4.11) package. Events from the two exposures were reprojected onto the same tangent point and merged using the CIAO merge_obs script. The image created from the merged events is shown in Figure 1. For sources of interest, spectra and associated response files were extracted separately for each observation and then fitted simultaneously using XSPEC v. 12.10.1.

3. Results

3.1. RNO 1B and 1C

Table 1 summarizes the X-ray properties of RNO 1B and 1C and other sources in their vicinity. For RNO 1B, the summed exposures yielded five events inside a $r = 1″.5$ extraction circle centered on its 2MASS position (2MASS J00364599 +6328529). Three events were detected in the first observation and two in the second with energies in the range of $E = 1.39–4.75$ keV and a mean energy of $E = 3.09 ± 1.40$ keV. For RNO 1C (2MASS J00364659 +6328574), a similar extraction yielded eight events, with

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3 Details on Chandra instrumentation and performance can be found in the Proposer’s Observatory Guide at cxc.harvard.edu/proposer/POG.
four detected in each observation and a range of \( E = 1.45–6.37 \text{ keV} \) and \( \bar{E} = 3.28 \pm 1.39 \text{ keV} \). Its X-ray centroid lies 0′′.7 west of the radio source Very Large Array (VLA) 1 (J003646.67+632853.7; Anglada et al. 1994). Background is negligible (<1 count within \( r = 1.5′′ \) extraction regions).

Event energy distributions are plotted as histograms in Figure 2. The outlier event at 6.37 keV for RNO 1C is noteworthy since it may be due to fluorescent Fe produced when cold gas near the star is irradiated by hard X-rays, as has been detected in FU Ori itself (Skrinner et al. 2006). But a spectrum of RNO 1C with more counts is needed to determine if fluorescent Fe emission near 6.4 keV is actually present.

We fitted the unbinned RNO 1C spectra with a simple absorbed single-temperature thermal plasma model (1T APEC) using the C statistic. Since the two spectra together provide only eight counts, they do not reliably constrain the absorption column density \( N_H \). It was thus stepped through values in the range of \( N_H = (1.7–4.5) \times 10^{22} \text{ cm}^{-2} \), corresponding to \( A_v \approx 9–24 \text{ mag} \) in order to span previous extinction estimates. We adopt the conversion \( N_H = 1.9 \times 10^{21} A_v \text{ cm}^{-2} \) obtained by averaging the slightly different conversions of Gorenstein (1975) and Vuong et al. (2003). The fits gave observed (absorbed) fluxes of \( F_{abs}(0.3–8 \text{ keV}) = 2.50(0.20) \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \). The derived plasma temperature, unabsorbed flux, and intrinsic X-ray luminosity \( L_x \) are sensitive to the assumed value of \( N_H \). The C statistic is minimized for \( N_H = (2.4–2.6) \times 10^{22} \text{ cm}^{-2} \) \( (A_v \approx 12.6–13.7 \text{ mag}) \) and \( kT \approx 3.2–3.7 \text{ keV} \). The luminosity estimate is log \( L_x(0.3–8 \text{ keV}) = 29.83(\pm 0.15) \text{ erg s}^{-1} \).

Since only five counts were detected for RNO 1B, we did not attempt spectral fits. Instead, we used the Portable Interactive Multi-Mission Simulator (PIMMS) to estimate the flux and \( L_x \) based on the ACIS-I count rate of 0.0845 c ks\(^{-1}\). A 1T APEC absorbed thermal plasma model was used, as for RNO 1C. The absorption was stepped through values in the range of \( N_H = (1.7–3.0) \times 10^{22} \text{ cm}^{-2} \), corresponding to \( A_v \approx 9–16 \text{ mag} \) (Staude & Neckel 1991; CR18). We used two different plasma temperatures, \( kT = 3 \) and 5.4 keV, typical of FUors and classical (accreting) T Tauri stars. For the above range of values, PIMMS predicts \( F_{abs}(0.3–8 \text{ keV}) = 1.60(0.20) \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \) and an unabsorbed luminosity of log \( L_x(0.3–8 \text{ keV}) = 29.64(\pm 0.15) \text{ erg s}^{-1} \). We emphasize that this \( L_x \) estimate is based on assumed values of \( N_H \) and \( kT \) that lie within reasonable ranges, but are not actual measurements. If \( N_H \) is greater than assumed (as could occur from cold gas along the line of sight that is not accounted for by \( A_v \)) or if \( kT \) is less, then higher \( L_x \) values are possible.

### 3.2. Other X-Ray Sources near RNO 1B/C

CXO J003647.1+632850.1 is a nine-count X-ray source whose position is nearly coincident with the infrared source RNO 1G (J003647.14+632849.95; Quanz et al. 2007). RNO 1G is a deeply embedded young stellar object originally identified in near-IR polarization maps by Weintraub & Kastner (1993). Both the X-ray and IR positions of RNO 1G are offset by \( \approx 0″.5 \) southeast of radio continuum source VLA 2 (Anglada et al. 1994). The X-ray source is hard with event energies in the range of \( E = 3.46–6.19 \text{ keV} \). Fits of the unbinned spectra with a 1T APEC model give a minimum C statistic for \( N_H = (1.5–2.0) \times 10^{22} \text{ cm}^{-2} \), corresponding to \( A_v \approx 79 \text{ mag} \) and high plasma temperatures of \( kT \approx 13–14 \text{ keV} \).

CXO J003647.4+632902.7 is a faint source offset \( \approx 0″.5 \) northeast of the 3.6 cm radio continuum source VLA 3. The radio source shows elongated structure and has a positive spectral index (Anglada et al. 1994), as commonly observed for driving sources of bipolar outflows. It was thus proposed by Anglada et al. that VLA 3 drives the bipolar molecular outflow in L1287 that was studied in millimeter molecular lines by Yang et al. (1991). There is no cataloged 2MASS source within 1″ of the X-ray position but IRAS 00338+6312 lies \( \approx 0″.9 \) southeast of the X-ray centroid. Four events were detected, of which three were detected in the first observation. The source is very weak with event energies in the range of \( E = 4.36–6.60 \text{ keV} \). The Chandra X-ray position may point to a deeply embedded (proto)star associated with the jet-like source VLA 3.

CXO J003647.3+632856.1 is a variable source which remarkably was only detected in the second Chandra observation (10 counts). This source is labeled as “anon” in Figure 1. There is no cataloged 2MASS counterpart. The radio source VLA 4 (J003647.39+632853.7) lies 2″3 to the south. The X-ray source is hard with event energies of \( E = 2.93–6.82 \text{ keV} \). Three events have energies of \( E = 6.36–6.82 \text{ keV} \), suggestive of Fe emission. This object is likely a heavily embedded magnetically active (flaring) young star or protostar that is only intermittently detected in X-rays. We fitted the unbinned spectrum with a 1T APEC model. No a priori information on \( A_v \) is available but we assumed high X-ray absorption and stepped through values of \( N_H = (1–40) \times 10^{22} \text{ cm}^{-2} \). The C statistic is minimized for \( N_H = (1–2) \times 10^{23} \text{ cm}^{-2} (A_v \approx 52 \text{ mag}) \) with \( kT \approx 2–4 \text{ keV} \).


| Chandra Position R.A., Decl. (J2000) | Name | Net Counts (cts) | $E$ ($E_{50}$) (keV) | Hardness | $F_{x, abo}$ (erg cm$^{-2}$ s$^{-1}$) | log $L_{x}$ (erg s$^{-1}$) | Offset (arcsec) |
|--------------------------------------|------|-----------------|----------------------|----------|-------------------------------|----------------------|---------------|
| J00 36 46.04+63 28 52.8              | RNO 1B | 5 ± 2           | 3.08 (3.09)          | 0.60     | 1.60(±0.20)е-15$^{e}$         | 29.64$^{e}$          | 0.34          |
| J00 36 46.55+63 28 57.3              | RNO 1C | 8 ± 3           | 3.28 (3.21)          | 0.75     | 2.50(±0.20)е-15$^{e}$         | 29.83$^{e}$          | 0.31          |
| J00 36 47.12+63 28 50.1              | RNO 1G | 9 ± 3           | 4.71 (4.59)          | 1.00     | 5.83(±0.20)е-15$^{e}$         | 30.41$^{e}$          | 0.22          |
| J00 36 47.41+63 29 02.7              | VLA 3  | 4 ± 2           | 5.42 (5.36)          | 1.00     | $^{*}$                        | $^{*}$               | $^{*}$         |
| J00 36 37.30+63 28 56.1              | anon   | 10 ± 3          | 4.58 (3.85)          | 1.00     | 9.88(±0.62)е-15$^{e}$         | 31.04$^{e}$          | ...           |

**Notes.** Data are based on merged events (0.3–7 keV) from Chandra Obs IDs 20135 and 21041, with a total live time of 59,143 ks. Tabulated quantities are: J2000.0 X-ray centroid position (R.A., decl.); object name; net counts and net counts error; mean $E$ and median ($E_{50}$) event energies; hardness = counts/(counts (0.3–7 keV))/counts (0.7–3 keV); absorbed X-ray flux (0.3–7 keV); unabsorbed X-ray luminosity at an assumed distance of 930 pc, and offset between Chandra and IR or VLA radio positions.

$^{e}$ $F_{x}$ and $L_{x}$ are estimated from 1T APEC PIMMS simulations assuming absorption $N_{H} = (1.7–3.0) × 10^{23}$ cm$^{-2}$ and $kT = 3.0–5.4$ keV.

$^{b}$ $F_{x}$ and $L_{x}$ are estimated from 1T APEC fits of unbinned spectra assuming $N_{H} = (1.7–4.5) × 10^{22}$ cm$^{-2}$.

$^{c}$ Insufficient counts to determine $F_{x}$ and $L_{x}$. $^{d}$ $F_{x}$ is based on a 1T APEC fits of unbinned spectra with $N_{H} = (1–2) × 10^{21}$ cm$^{-2}$ and $kT = 1.6–4.1$ keV.

**Figure 2.** X-ray event energy histograms for RNO 1B/1C using energy bin widths of 1 keV.

**Non-Detections.** We find no significant X-ray emission at the position of the source tentatively identified as RNO 1D by Weintraub et al. (1996) or at the position of RNO 1F (Quanz et al. 2007).

**4. Discussion**

**4.1. RNO 1B and 1C in Context**

The Chandra data show similar X-ray properties for RNO 1B and 1C. There is no significant difference in the number of events detected for the two stars or in their mean event energies to within the uncertainties. Spectra with a larger number of counts will be needed to determine if real differences exist. Since no pre-outburst X-ray spectra are available for RNO 1B (or for FUors in general), we do not know whether its X-ray properties were affected by the 1978–1990 eruption.

Our $L_{x}$ estimates for RNO 1B and 1C make them the least X-ray luminous FUors detected to date, about a factor of 10 less luminous than the X-ray bright sources FU Ori (log $L_{x} = 30.68$ erg s$^{-1}$), V1735 Cyg (log $L_{x} = 30.80$), and V960 Mon (log $L_{x} = 31.12$). The faint X-ray emitting FUor-like source L1551 IRS 5 has a lower $L_{x}$ than RNO 1B and 1C but its X-ray emission is offset from the obscured central object and probably originates in its jet (Favata et al. 2002; Bally et al. 2003; Schneider et al. 2011). Upper limits for a few undetected FUors are comparable to or less than the $L_{x}$ values of RNO 1B and 1C. For example, V883 Ori was undetected by XMM-Newton at log $L_{x} \leq 29.65$ erg s$^{-1}$ (Obs ID: 0205150501; PI: S. Skinner). Also, three archived Chandra ACIS-I exposures with a combined live time of 71,675 ks (Obs IDs 9919, 10811, 10812; PI: T. Allen) captured V733 Cep far off-axis but it was not detected. This star erupted in 1971 or earlier and has optical and near-IR spectra very similar to FU Ori (CR18). Based on all three Chandra exposures, we obtain a conservative upper limit of log $L_{x}(0.3–8$ keV) $\leq 28.95$ erg s$^{-1}$ at $d = 800$ pc (CR18) assuming a thermal plasma spectrum with $kT = 3$ keV and extinction as large as $A_{v} = 11.5 \pm 1$ mag (CR18), equivalent to $N_{H} \approx 2.2 \times 10^{22}$ cm$^{-2}$. If the Gaia DR2 distance of 669$^{+50}_{-43}$ pc for V733 Cep is adopted then a more stringent upper limit of log $L_{x}(0.3–8$ keV) $\leq 28.80$ erg s$^{-1}$ is obtained. The derived upper limits are sensitive to the assumed values of $N_{H}$ and $kT$. If the actual $N_{H}$ is higher or $kT$ lower than assumed above, then the upper limits increase. Despite its spectroscopic similarity to FU Ori, it is much fainter in X-rays and so far undetected down to rather stringent upper limits.

As shown in Figure 3, the X-ray luminosities of RNO 1B and 1C are comparable to accreting classical T Tauri stars (Preibisch et al. 2005; Telleschi et al. 2007) despite the fact that FUors have much higher bolometric luminosities. At our assumed distance of 930 pc, the results of Gramajo et al. (2014) give $L_{bol}$ = 527 $L_{x}$ (RNO 1B) and 646 $L_{x}$ (RNO 1C). These $L_{bol}$ values are quite high, even for FUors (CR18). It is thus clear that high $L_{bol}$ for FUors does not necessarily translate into high $L_{x}$. By comparison, a general trend for an increase in $L_{x}$ with $L_{bol}$ is seen in classical T Tauri stars, albeit with large scatter in $L_{x}$ (Figure 3). Since $L_{bol}$ in FUors is dominated by a luminous accretion disk, any possible dependence of $L_{bol}$ on the luminosity of the central star ($L_{x}$) will be difficult to establish without reliable estimates of $L_{x}$.

Similarly, a correlation with stellar mass $L_{x} \propto M_{x}$ exists for classical T Tauri stars (Preibisch et al. 2005; Telleschi et al. 2007), but no such correlation has yet been established for FUors since their stellar masses are not well known. There is even disagreement as to whether the prototype FU Ori is a subsolar mass star (Zhu et al. 2007) or a more massive object (Herbig et al. 2003). But in a few cases, pre-outburst optical and near-IR observations show that the progenitor was a young late-type star. For example, HBC 722 (=LkHα 188-
G4 = V2493 Cyg) was classified as a K7-M0 star by Cohen & Kuhi (1979), implying a subsolar mass progenitor.

4.2. Comments on FUor X-Ray Emission

Since some FUors are detected as luminous X-ray sources whereas others are undetected down to rather stringent upper limits (e.g., V733 Cep), we would like to know what factor(s) ultimately govern their X-ray properties. Since the stars themselves are generally heavily obscured, we lack sufficient data about stellar properties (e.g., mass, stellar luminosity, rotation period, magnetic field strength, accretion rate) to answer this question. However, their bolometric luminosities have been determined and as noted above the $L_\text{bol} \propto L_\text{X}$ relation seen in classical T Tauri stars does not hold for FUors.

Previous observations show that the detected X-ray emission of FUors cannot be due entirely to accretion shocks. Even though their accretion rates are as high as $M_{\text{acc}} \gtrsim 10^{-5} M_\odot$ yr$^{-1}$ during outbursts, accretion shock emission is expected to produce only cooler X-ray plasma at characteristic temperatures of $T_{\text{shock}} \sim 1$–2 MK ($kT_{\text{shock}} \sim 0.1$–2 keV) for plausible infall speeds of a few hundred km s$^{-1}$ (Skinner et al. 2009). A similar conclusion holds for shocked winds or jets assuming terminal speeds of a few hundred km s$^{-1}$ (Raga et al. 2002). However, it is worth noting that soft accretion shock emission from very cool plasma would be difficult to detect when viewed through the high absorption of some FUors. Such objects include RNO 1C whose near-IR colors (Figure 4) and high $A_v$ estimates (Section 1) indicate heavy reddening. Furthermore, additional X-ray absorption from dust-depleted gas that is not accounted for by $A_v$ may be present. This is probably the case for FU Ori, which shows X-ray evidence for cold gas near the star in the form of fluorescent Fe I X-ray emission (Skinner et al. 2006). Another example is HBC 722, which showed apparently variable circumstellar X-ray absorption by dust-depleted gas in early outburst (Liebhart et al. 2014).

Even though the hot X-ray plasma detected in FUors cannot be attributed to accretion shocks, FUor X-ray properties might be affected by accretion. This could occur if enhanced accretion during optical/IR outbursts alters the magnetic field topology or stellar structure, as has been suggested for accreting T Tauri stars (Preibisch et al. 2005) and the eruptive young star V1118 Ori (Audard et al. 2010).

Fits of the X-ray component detected in FUors with thermal plasma models typically give $kT \gtrsim 3$ keV ($T \gtrsim 35$ MK). Our fits of the low-count RNO 1C Chandra spectrum are consistent with such high temperatures. In the case of FU Ori, the X-ray count rate in the hard 2–8 keV band varied on a timescale of less than one day (Skinner et al. 2010). Such variable hard emission clearly points to magnetically controlled processes. The cause of the variability is not known, but the <1 day timescale is suggestive of magnetic-reconnection flares. Even so, the factor of ~2 variability in the hard-band count rate of FU Ori is rather modest compared to the powerful impulsive X-ray flares that have been detected in some T Tauri stars and class I protostars.

X-ray monitoring of FUors in the time domain is still quite limited. Long-term X-ray monitoring is needed to search for powerful impulsive X-ray flares and for evidence of periodic or quasi-periodic emission. Periodic emission could be induced by stellar rotation and would provide insight into poorly known rotation periods, as has been demonstrated for the protostar V1647 Ori (Hamaguchi et al. 2012). Orbital X-ray modulation could also be present if some FUors are close binaries, as suggested by Reipurth & Aspin (2004).

5. Summary

Chandra observations of the close pair of similar FUor-like stars RNO 1B and 1C reveal faint X-ray emission with intrinsic luminosities of $\log L_\text{X} = 29.64$–29.83 erg s$^{-1}$, making them the faintest X-ray detections among FUors to date. Their low $L_\text{X}$ in combination with high $L_\text{bol}$ shows that the $L_\text{X} \propto L_\text{bol}$ relation present in classical T Tauri stars does not carry over to FUors. Their X-ray spectral properties are not well constrained due to the low number of detected counts but our analysis suggests high plasma temperatures of $kT \gtrsim 3$ keV and high absorption.
of $N_H \gtrsim 10^{22} \text{ cm}^{-2}$, the latter being consistent with existing $A_v$ estimates. The high plasma temperature implies that the detected X-ray emission is due to magnetic processes, not accretion shocks or shocked winds.

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Facility: Chandra (ACIS).

Software: CIAO (Fruscione et al. 2006), XSPEC (Arnaud 1996).

ORCID iDs
Stephen L. Skinner @ https://orcid.org/0000-0002-3025-3055
Manuel Güdel @ https://orcid.org/0000-0001-9818-0588

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