Radio *Videos* of Orion Protostars

(WITH X-RAY COLORS!)

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Abstract

High-energy processes in Young Stellar Objects (YSOs) can be observed both in X-rays and in the centimetric radio wavelength range. While the past decade has brought a lot of progress in the field of X-ray observations of YSOs, (proto)stellar centimetric radio astronomy has only recently begun to catch up with the advent of the newly expanded Karl G. Jansky Very Large Array (JVLA). The enhanced sensitivity is fundamentally improving our understanding of YSO radio properties by providing unprecedented sensitivity and thus spectral as well as temporal resolution. As a result, it is becoming easier to disentangle coronal-type nonthermal radio emission emanating from the immediate vicinity of YSOs from thermal emission on larger spatial scales, for example ionized material at the base of outflows. Of particular interest is the correlation of the by now relatively well-characterized X-ray flaring variability with the nonthermal radio variability. We present first results of multi-epoch simultaneous observations using Chandra and the JVLA, targeting the Orion Nebula Cluster and highlighting the capabilities of the JVLA for radio continuum observations of YSOs.

Chandra and the NEW! Karl G. Jansky Very Large Array

Using the newly expanded continuum bandwidth of the VLA, we have obtained about **24 hours of simultaneous VLA and *Chandra* observations** of the Orion Nebula Cluster (ONC). These were observed in four epochs scheduled within four consecutive days. The VLA observations were obtained in the 4-8 GHz band, providing a field of view of up to 11' FWHM, almost matching *Chandra*-ACIS. The data rates are... *high*.

Why simultaneous? While there is a lot of interest in the new centimeter radio view of the ONC alone, any study of the connection between X-ray and radio variability (e.g., flaring) ideally requires simultaneous multi-wavelength observations. The ONC provides a large number of sources accessible in a single VLA pointing.

The Orion Nebula Cluster

While several simultaneous X-ray and radio observations of young stellar objects (YSOs) have been carried out previously (e.g., Gagné et al, 2004, Forbrich et al. 2007, 2011), they were primarily limited by low numbers of sources and insufficient radio sensitivity to identify nonthermal emission. The ONC provides a sample of 77 known radio sources in the same field of view (Zapata et al. 2004, "old" VLA data).

Credit: X-ray: NASA/CXC/Penn State/E.Feigelson & K.Getman et al.; Optical: NASA/ESA/STScI/M. Robberto et al.

Science questions

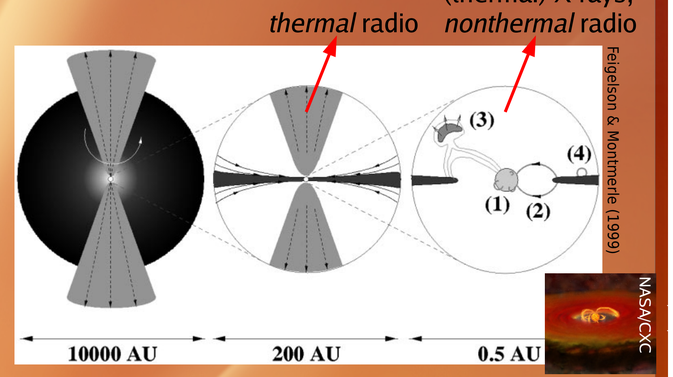
- When do protostars become radio-active in the cm range?
- What is the census of *non-thermal* emission in particular? Why did we so far see so few of those? S/N?
- What are the statistics of radio *flaring* for young stellar objects?
- Are radio flares correlated with X-ray flares?

Why now? Now or never!

In the X-ray range, high-energy processes in young stellar objects (YSOs) have been studied in considerable detail over the past decade, using *Chandra* and XMM-*Newton*. X-ray flaring, for example, is now well characterized. At the same time, radio studies of YSOs have been hampered by insufficient sensitivity for spectral and variability studies. With the advent of the newly expanded Karl G. Jansky Very Large Array, (proto-)stellar radio astronomy is entering a new age of exploration.

Radio has no future. X-ray is a hoax. – *Lord Kelvin*

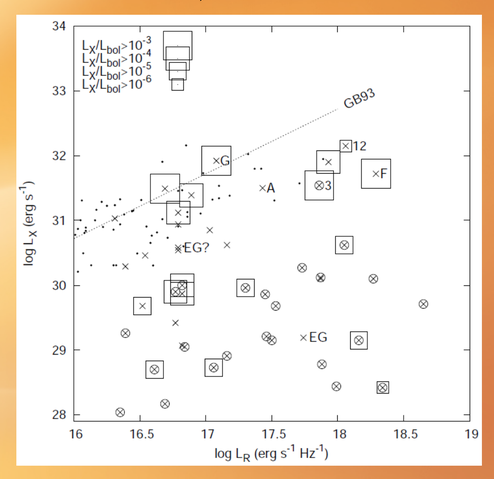
The radio–X-ray connection



Both X-rays *and* nonthermal radio emission, usually gyro-synchrotron radiation, probe the i**nnermost vicinities** of protostars.

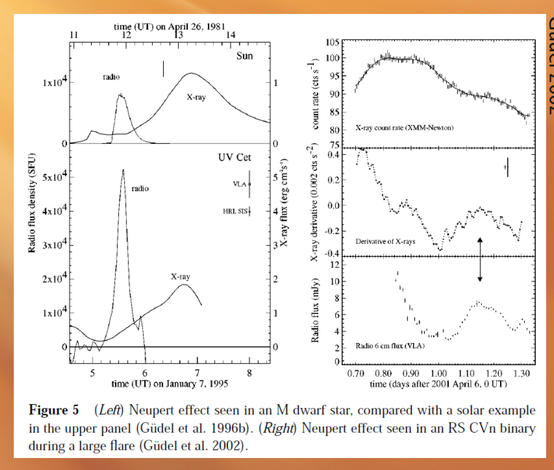
The correlation of these two types of emission is studied either with time-averaged radio and X-ray luminosities or with flare observations.

Güdel & Benz (1993) found an empirical relation between the radio and X-ray luminosities of a wide range of active stars. The Orion sources fall below this relation, but the older VLA data did not allow for a distinction between thermal and nonthermal emission (Forbrich & Wolk 2013).



With sufficient time resolution, a correlation of the radio and X-ray light curves in flares according to the **Neupert effect** (Neupert 1968) has been observed on the Sun and a few other stars. Essentially, the radio emission is thought to trace the initial energy injection of the flare which is heating the gas to emit thermal X-rays:

$$L_R(t) \propto \frac{d}{dt} L_X(t)$$



Güdel 2002

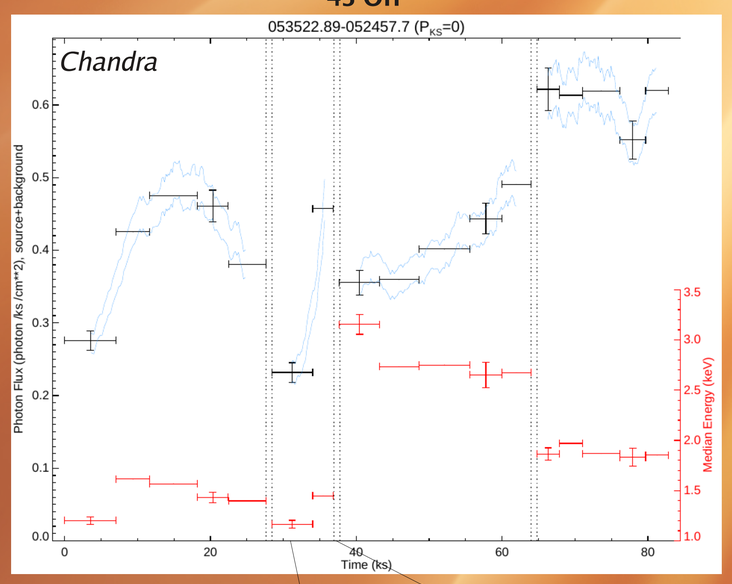
Figure 5 (*Left*) Neupert effect seen in an M dwarf star, compared with a solar example in the upper panel (Güdel et al. 1996b). (*Right*) Neupert effect seen in an RS CVn binary during a large flare (Güdel et al. 2002).

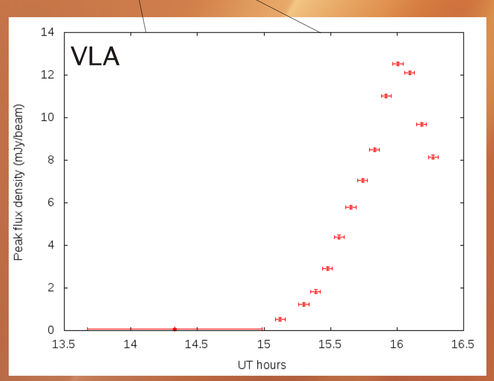
Data reduction and first results

The data reduction of the Chandra observations has been carried out using acis_extract (Broos et al. 2010). This facilitates the comparison with the Chandra Orion Ultra-deep Project (COUP; Feigelson et al. 2005, Getman et al. 2005). Source extraction was carried out on the COUP sources, although additionally, a few new, deeply embedded sources were found. The reduction of the VLA data is ongoing using the CASA software environment.

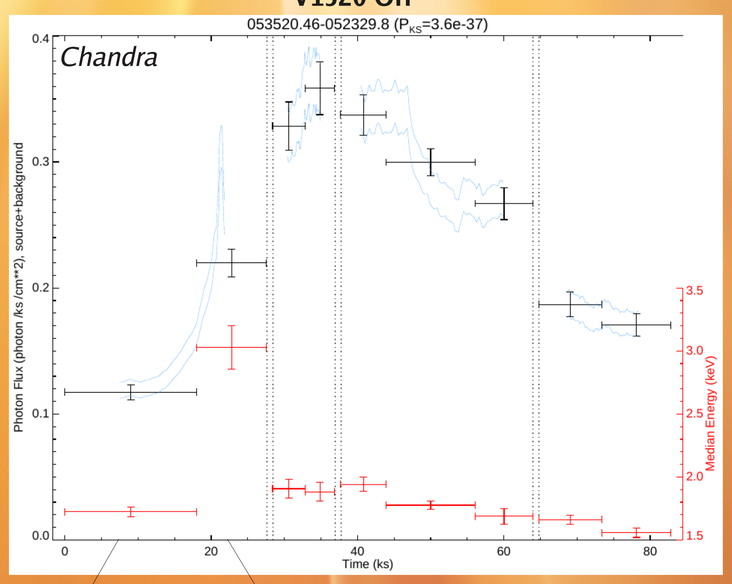
With the new VLA, considerably more radio sources are detected than were previously known. We here show two first examples of radio and X-ray variability of two very different Orion sources. One is 43 Ori, an early B star, and the other is V1520 Ori, a binary class II T Tauri star with a separation of 0.86" (Daemgen et al. 2012). Already these examples indicate a connection between radio and X-ray flares, but a complex one.

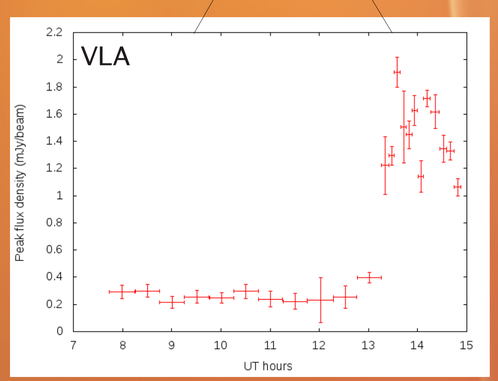
43 Ori





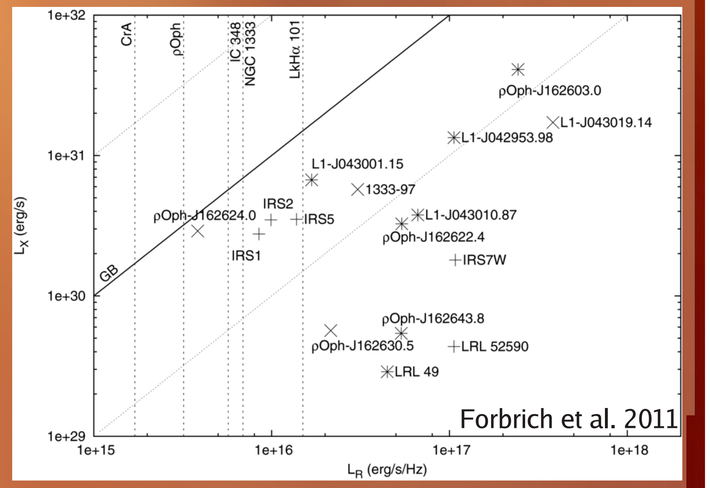
V1520 Ori





The median photon energy in the X-ray light curves shown above indicates the hardness (or color) of the X-ray emission. Toward the end of the flare of V1520 Ori, when the radio emission sets in, the X-ray photon energy rises very significantly.

The radio–X-ray connection in YSOs



Plot of the X-ray and radio luminosities of all YSOs that have been simultaneously detected in both the X-ray and radio ranges by *Chandra* and the VLA, prior to this program. They fall below the empirical relation, but which of these, apart from CrA-IRS5 are nonthermal?

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