INVESTIGATIONS OF MAGNETIC ACTIVITY ACROSS YSO CLASSES: MULTIWAVELENGTH OBSERVATIONS OF THE STAR-FORMING REGIONS L1630 AND L1622

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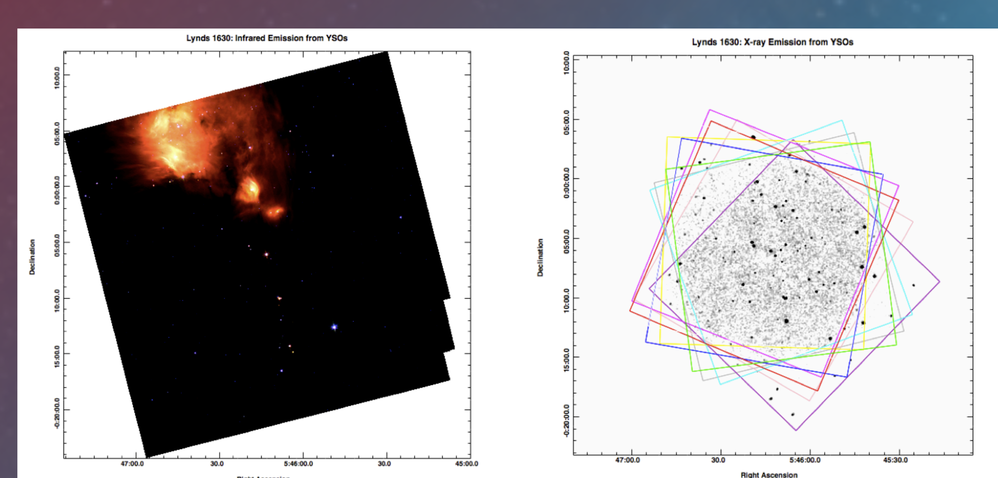
The role of magnetic fields in star formation is presently the subject of intense debate. A combination of X-ray and infrared/submm observations of young stellar objects (YSOs) in active regions of star formation can elucidate the presence and strength of magnetic fields and the likely influence of such fields on protostellar collapse and the formation of circumstellar disks. Here, we present combined Chandra X-ray, Submillimeter Array (SMA), and archival infrared observations of L1630 and L1622, two particularly diverse star-forming regions in Orion. We have characterized the X-ray activity of dozens of YSOs in L1630, and conducted an SMA continuum and line imaging study to determine the submillimeter emission properties of X-ray-emitting YSOs in selected regions of the cloud. We have also established the association of X-ray activity and SMA continuum sources with the components of the HBC 515 multiple system in L1622. This system is composed of a very young (age < 1 Myr) intermediate-mass (~2 Solar mass) binary, which evidently has already dissipated its circumstellar disk; a low-mass protostar surrounded by a thick envelope of gas and dust; and two more widely separated, low-mass, pre-main sequence stars. It is hence an excellent system for testing various theories describing disk dispersal and multiple system interaction in the early stages of the star formation process.

The origin of stellar magnetic fields is generally well described by dynamo theory. The interaction between convection and protostellar rotation produces a magnetic dynamo at the base of the convective zone which is likely responsible for a host of stellar magnetic phenomena such as magnetic spots, a thin chromosphere and magnetically confined coronal plasma occasionally undergoing flares (Güdel & Nazé 2009, A&A Review, 17, 309). Such processes ultimately result in coronally generated X-ray emission.

Magnetic fields also likely play a significant role in accretion and outflow processes throughout all stages of star formation, from core collapse to accretion of disk material to the propagation of jets and winds. Potential insight into young star magnetic fields can be provided by the radio, infrared and X-ray properties of observed young stellar objects (YSOs).

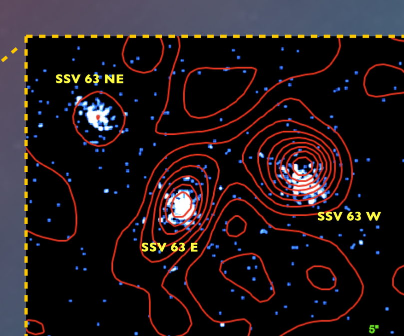
Lynds 1630

As part of the Orion B molecular cloud, L1630 is a diverse star forming region (d~ 450 pc) with dense cores of molecular gas, high velocity outflows, T Tauri stars, bright reflection nebulae and Herbig-Haro objects (Simon et al. 2004 and ref therein).

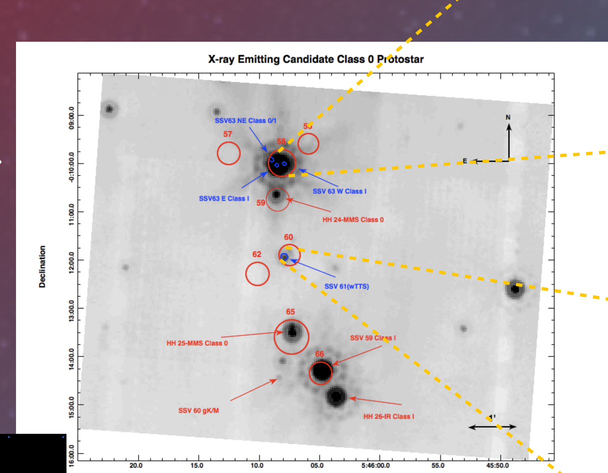


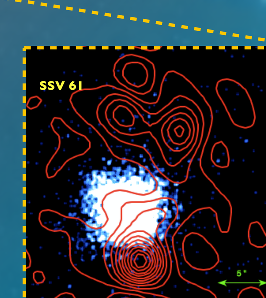
We have pursed a multiwavelength campaign to characterize the X-ray variability and disk dust properties of YSOs in all stages of young stellar evolution. Above is a Spitzer 3 color (3.6, 4.5 and 8.0 µm) image (left) and an 11 Chandra X-ray merged observation (right) of L1630. We have established the association of X-ray activity and submm continuum sources (see below), including a rare X-ray emitting candidate Class 0 protostar, probing violent magnetic effects in the earliest stages of star formation.

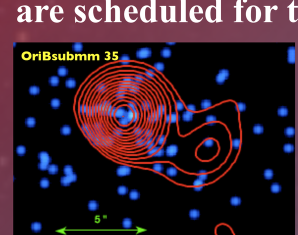
Recent SMA observations have revealed submillimeter features spatially coincident with several deeply embedded protostars including SSV 63NE, a rare X-ray emitting Class 0 candidate. Below is a Spitzer 24 µm image of a subset of L1630. Red circles represent Mitchell et al. (2001) 850 µm submm sources and blue circles represent Chandra X-ray detections (Principe et al. 2013 in prep).

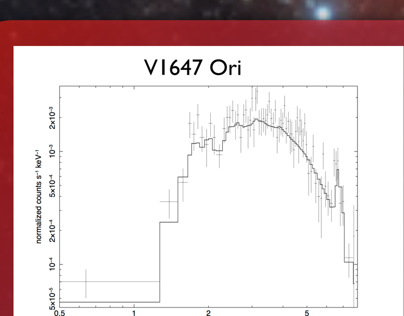


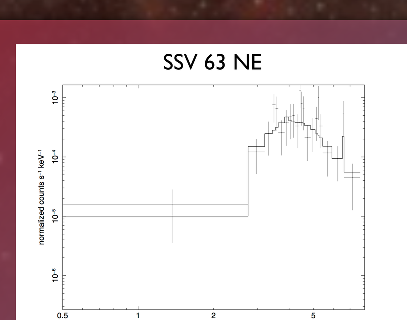
Given the proximity of YSOs with potentially strongly contrasting infrared class in L1630, we are conducting a campaign of high-resolution IR and submm imaging of the region with SOFIA and the Submillimeter Array. Preliminary results of the SMA observations are displayed here. SOFIA observations are scheduled for this fall.



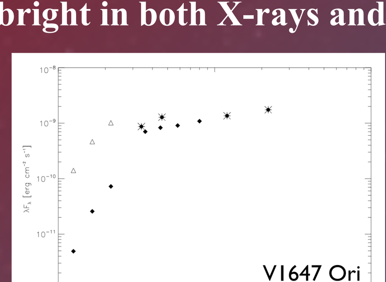


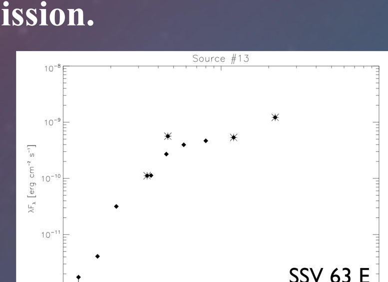




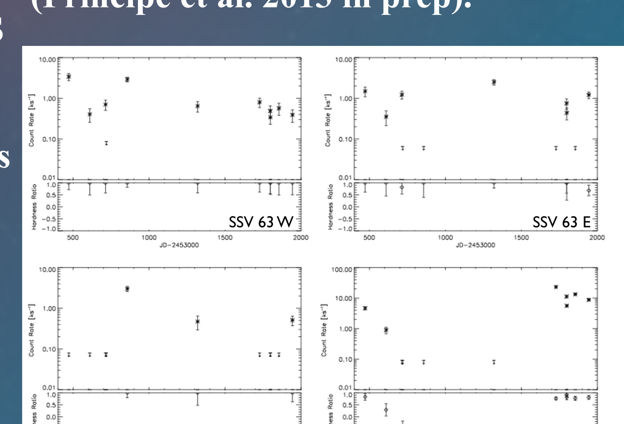


Highly absorbed X-ray spectra (histogram) of two embedded protostars are shown above. Model fitting (solid line) likely indicates large absorption (~10^{23} cm^{-2}) likely due to circumstellar and intervening molecular gas. SEDs (below) were constructed from archival 2MASS (diamond), Spitzer (diamond), WISE (asterisks) and post outburst Gemini JHK photometry (triangles). They highlight the disk dust excess of these protostars and the eruptive nature of V1647 Ori that is bright in both X-rays and submm emission.



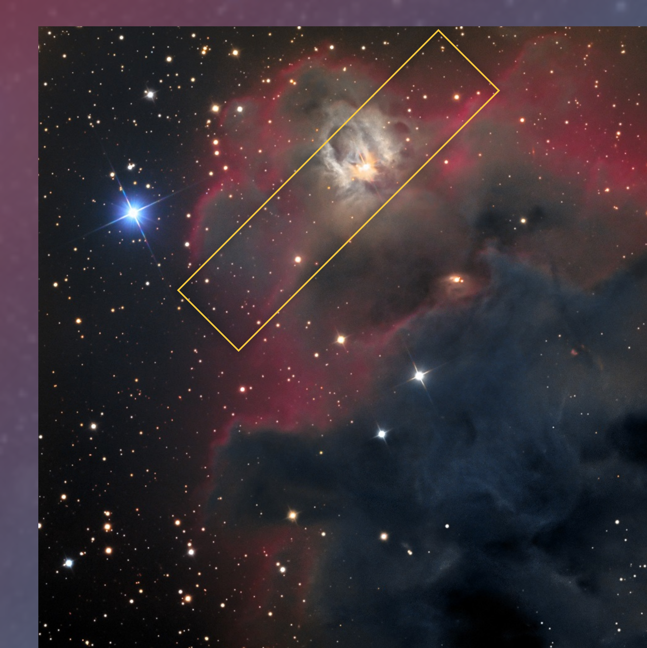


Both coronal activity and star-disk interactions are phenomena that can plausibly cause X-ray variability. Protostars in L1630 show order of magnitude variations over the course of four years (below) possibly indicative of violent magnetic events during the earliest stages of star formation (Principe et al. 2013 in prep).



Lynds 1622

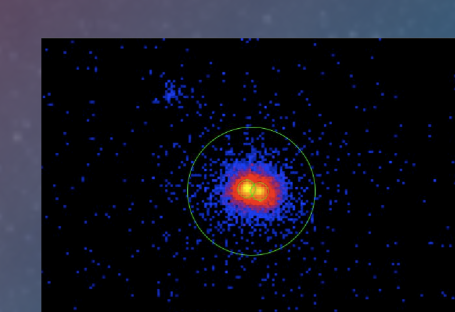
The star forming region L1622 is part of the Orion B molecular cloud complex and is located in the tenuous outer layers of Barnard's loop. Much like L1630, L1622 displays many signs of active star formation (Reipurth et al. 2010 and ref therein). At a distance of ~500 pc, L1622 contains a number of young stars including multiple systems with many components. Spitzer observations have led to the discovery of many infrared excess objects, 32 of which are pre-MS stars (Reipurth et al. 2008).

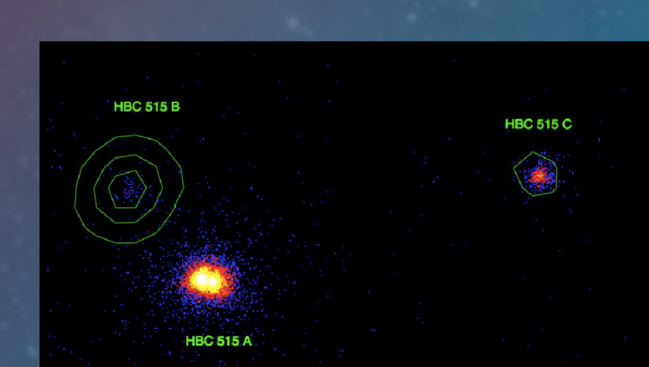


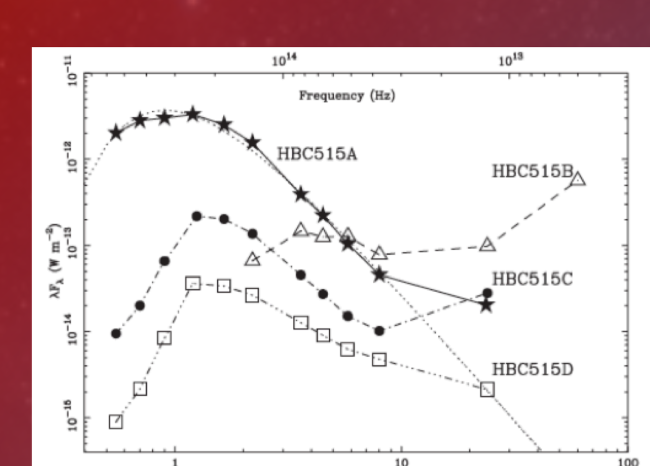
An optical LRGB image (above; Adam Block, University of Arizona) displays the bright reflection nebula associated with HBC 515. Our ~30 ks Chandra X-ray observation of this region is overlaid (yellow box).

We have pursed a multiwavelength campaign to characterize the X-ray and submillimeter properties of the HBC 515 multiple system, This system is composed of a very young (age < 1 Myr) intermediate-mass (~2 Solar mass) binary, which evidently has already dissipated its circumstellar disk; a low-mass protostar surrounded by a thick envelope of gas and dust; and two more widely separated, low-mass, pre-main sequence stars.

A Spitzer 3.6 µm observation of all four components of HBC 515 is shown below (Reipurth et al 2010). All four members were detected in the ~30 ks Chandra X-ray observation (right). The binary HBC 515 A, separated by ~0.5 arc seconds, is resolved and is one of the X-ray-brightest late-type stars in Orion. HBC 515 B is marginally fainter in X-rays than HBC 515 A, likely due to the presence of a gas envelope. SMA 1.3 millimeter observations of this region (bottom right) shows dust continuum emission (green contours) verifying the highly embedded environment of HBC 515 B (Sacco et al. 2013 in prep).

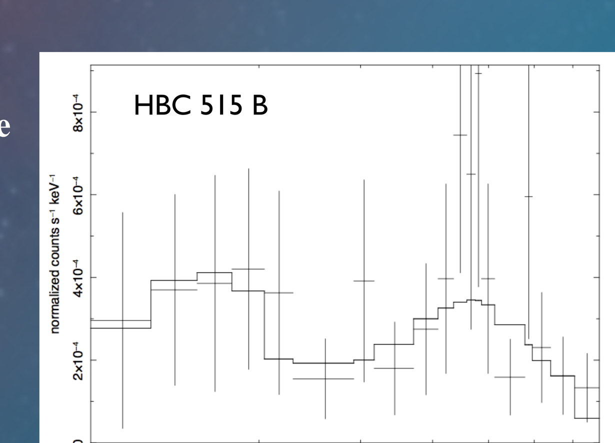






SEDs for the four HBC 515 members are shown (left) from Reipurth et al. (2010). Spitzer color-color classification suggests HBC 515 B is at a stage of young stellar evolution between Class I and Class II. However, considering its highly absorbed X-ray spectrum and 1.3 mm detection, it is likely a Class I source.

The X-ray spectrum (histogram) of HBC 515 B is shown to the right. It displays two temperature components at 2 and 5 keV, respectively. The soft component could be produced from plasma heated up by shocks from a protostellar jet interacting with the circumstellar environment. The hard component is likely produced by the heavily absorbed protostar (Sacco et al. 2013 in prep). This unusual spectrum has been observed in other young protostars driving protostellar jets (Kastner et al. 2005).



This research is supported by Chandra X-ray Science Center grants to RIT. Background image by Rogelio Bernal Andreo.