Time resolved X-ray spectral analysis during optical dips and accretion bursts in stars with disks of NGC2264 from Chandra/ACIS-I and CoRoT data

Time resolved X-ray spectral analysis during optical dips and accretion bursts in stars with disks.

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CoRoT was a pioneering stellar seismology and exoplanet hunting mission that ran from 2006 to 2014.

CoRoT collected about 160000 light curves with a cadence of 512 sec, or 32 sec for the brighter sources.

CoRoT observed stars in two regions with 10° diameter close to the galactic center and anticenter.
About 2000 sources up to O7V: the only cluster within 1 kpc from the Sun, besides the ONC, with such a large mass spectrum.

NGC 2264 is the only young cluster (1-5 Myrs, 760 pc, low average extinction) falling in one of the CoRoT eyes: A unique opportunity to study variability in Pre-Main Sequence stars.

Optical image of NGC 2264
The Coordinated Synoptic Investigation of NGC2264

An unprecedented cooperative project involving simultaneous observations of NGC 2264 with 15 ground and space telescopes, from X-rays to mid-infrared. [e.g. Cody et al. 2014]

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Instrument</th>
<th>Dates</th>
<th>Band(s)</th>
<th>Time Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spitzer</td>
<td>IRAC/mapping</td>
<td>Dec. 3, 2011–Jan. 1, 2012</td>
<td>3.6 µm, 4.5 µm</td>
<td>101 min</td>
</tr>
<tr>
<td>Spitzer</td>
<td>IRAC/staring</td>
<td>Dec. 3; Dec. 5–6; Dec. 7–8; Dec. 8–9, 2011</td>
<td>3.6 µm, 4.5 µm</td>
<td>15 s</td>
</tr>
<tr>
<td>Chandra</td>
<td>ACIS-I</td>
<td>Dec. 3, 2011–Dec. 9, 2011</td>
<td>0.5–8 keV</td>
<td>~3.2 s²</td>
</tr>
<tr>
<td>USNO 40-inch telescope</td>
<td>CCD</td>
<td>Nov. 22, 2011–Mar. 9, 2012</td>
<td>J</td>
<td>47–54 epochs</td>
</tr>
<tr>
<td>NMSU 1m telescope</td>
<td>CCD</td>
<td>Oct. 12, 2011–Mar. 4, 2012</td>
<td>I</td>
<td>44 epochs</td>
</tr>
<tr>
<td>OAN 1.5m telescope</td>
<td>CCD</td>
<td>Jan. 10, 2012–Feb. 15, 2012</td>
<td>J,H,K</td>
<td>40–52 epochs</td>
</tr>
<tr>
<td>CAHA 4.5m telescope</td>
<td>LAICA</td>
<td>Jan. 25–26, 2012</td>
<td>u, r</td>
<td></td>
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</tbody>
</table>

300 ksec in four epochs of **Chandra/ACIS-I** exposure during CoRoT observation

A total of 694 X-ray sources validated, **86 known stars with disks.**
Variability in stars with disks

Collection of CoRoT light curves of stars with disks in NGC2264 [Cody et al. 2014]
Optical variability in stars with disks – disk warps

- Recurrent occultation of the central star by warps in the circumstellar disk located close (few 0.1 AU) to the co-rotation radius, stable when due to misaligned rotation and magnetic axis (AA Tau variability) [e.g. Bouvier et al. 1999].

- 40% of the stars with inner disks in NGC2264 are characterized by AA Tau-like variability [Alencar+2010]

- Defined as “dippers” by Cody et al. 2015 (21.5% of the whole sample)

Two stars with dips observed with CoRoT in NGC2264 [Cody et al. 2014]
Optical variability in stars with disks - accretion

- Accretion can be unsteady and produce short (hours to ~1 day) bursts (5%-50% quiescent level) [Stauffer et al. 2014]. 13% of stars with disks in NGC2264 (bursters).

  ![Graph showing optical variability](image1)

- Accretion streams, which may contain also dust, can obscure the central star and produce narrow dips with $\text{FWHM}_{\text{dip}}/P_{\text{star}} < 0.25$ [Stauffer et al. 2015].

  ![Simulation of accretion](image2)

- The energetic optical emission from accretion hot spots ($10^4$K blackbody) can be modulated by stellar rotation.

  *Simulation of unsteady accretion onto a $1M_\odot$ class II star [Colombo et al. in prep.]*
Optical variability in stars with disks – stellar activity

- Rotational modulation of photospheric spots.
- Intense flares observed in PMS stars [e.g, Flaccomio et al. 2003]; they can be so powerful to be compatible with very large loops reaching the surface of the inner disks [Favata et al. 2005].

Stars with periodic variability (and one flare) observed with CoRoT in NGC2264 [Cody et al. 2014]
X-ray variability in stars with disks

- Accretion contributes to soft X-rays emission [e.g. Kastner et al. 2002], produced in the accretion shocks (e.g. TW Hya and BP Tau, [Kastner et al. 2002; Stelzer & Schmitt 2004; Schmitt et al. 2005; Argiroffi et al. 2011; Curran et al. 2011]). But difficult to distinguish from the coronal soft X-ray emission and self-absorption is crucial [Argiroffi et al. 2011; Bonito et al. 2014].

- Soft X-ray emission from accretion spots can be rotationally modulated (e.g. V4046 Sgr [Argiroffi et al. 2012]).

- Variable absorption of the coronal emission by circumstellar and accreting material [e.g., Flaccomio et al. 2010].

- The most evident source of X-ray variability is flares.

- X-ray emission from coronal active regions can be modulated by stellar rotation [e.g. Flaccomio et al. 2005].
Variability NGC 2264 stars with disks

Collection of CoRoT light curves of stars with disks in NGC2264 [Cody et al. 2014]
Global Optical vs. X-ray variability observed

Comparison of the flux observed in two consecutive Chandra epochs in:

i) Stars with at least two epochs with more than 10 X-ray counts

ii) Stars with variability classified by Cody et al. 2015: blue (stars with dips), red (bursters), black (the others)
The analysis – CoRoT light curves as template

We used the CoRoT light curves to isolate time intervals when interesting phenomena occurred (e.g. bursts and dips), extracted the X-ray photons in these intervals and calculated the “time resolved X-ray properties”
We analysed 24 stars with dips and good X-ray data. In 9 stars NH is observed to increase during the optical dip. Evidence for absorption of X-rays by circumstellar material.
The analysis – dippers

In 6 dips we calculated $N_H$, $A_V$, $\text{FWHM}_{\text{dip}}$, and also have $P_{\text{star}}$ [Venuti et al. in prep.], and estimated that they are due by gas-rich (i.e. $\log(N_H/A_V) > 22$) and narrow ($\text{FWHM}_{\text{dip}}/P_{\text{star}} < 0.15$) structures, likely accretion streams. However, our sample is strongly biased.
The analysis – bursters

We analysed 20 stars with bursts and good X-ray data.

In 5 cases, during the bursts:

- The X-ray spectral fit requires a 2T thermal model
- Low E10% and soft X-ray emission in excess compared to the best-fit 1T model
The analysis – bursters

Assuming:

- $T_{\text{soft}} = T_{\text{post}}$ and strong shock scenario;
- Ignoring energy loss during accretion;

In two cases (Mon-370 and Mon-808) we could calculate $v_{\text{preshock}}$ as:

$$v_{\text{pre}}^2 = \frac{16 k T_{\text{post}}}{3 \mu m_H}$$

In these two stars:

- $T_{\text{soft}}$ about 0.15 keV and $v_{\text{preshock}} = 350-360$ km/h
- free fall radii about $2R_{\text{star}}$, below the expected co-rotation radius (5-10 $R_{\text{star}}$ [Hartmann et al. 1998, Shu et al. 2000])

This is the configuration suggested for the unsteady accretion [e.g. Romanova et al 2012]
We performed 2T Thermal plasma model X-ray spectral fitting to all the time-intervals we defined.

We compared the normalizations of soft and hard components

We found larger soft-component normalizations during the optical bursts than in the time intervals defined for non accreting stars
CONCLUSIONS

• Variability in class II YSOs is an excellent probe to study the physical properties of the inner region of the disks and the accretion streams.

• By analysing optical and X-ray simultaneous variability in stars with disks in NGC 2264 we have found:
  • Evidence for increasing X-ray absorption during optical dips, which are likely due to narrow gas-rich accretion columns
  • Evidence for increasing soft X-ray emission during the optical accretion bursts
  • In two cases data support unsteady accretion geometry, but under several strong assumptions
“PLEASE HELP ME” - slides
Chandra/ACIS-I Fields
Mon-370; Average spectrum

- 1T thermal plasma model
- 2T thermal plasma model

Normalized counts $s^{-1} \text{ keV}^{-1}$

Energy (keV)