

A multiwavelength view of star-disk interaction in NGC 2264 ^{*}

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Variability is a signature property of cool young stars, particularly for those surrounded by disks. Traditional single-band time series display complex features associated with accretion, disk structure, and accompanying stellar activity, but these processes are challenging to model. To make progress in connecting observed time domain properties with the underlying physics of young stars and their disks, we have embarked on an unprecedented multiwavelength monitoring campaign: the Coordinated Synoptic Investigation of NGC 2264 (“CSI 2264”). Beginning in December 2011, CSI 2264 has acquired 30 continuous days of mid-infrared time series from *Spitzer*, simultaneous optical monitoring from CoRoT and *MOST*, X-ray observations with Chandra, as well as complementary data from a number of ground-based telescopes. The extraordinary photometric precision, cadence, and time baseline of these observations enable detailed correlation of variability properties at different wavelengths, corresponding to locations from the stellar surface to the inner AU of the disk. We present the early results of the program, and discuss the need for further modeling efforts into young stars and their disks.

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1 The promise of multiwavelength time series monitoring of young stars

The canonical picture of a young accreting star (see Hartmann 1998) involves emission at a wide range of wavelengths, characterizing various regions from the central object to the outer reaches of its disk. Stellar flux comes primarily in the optical, with some contributions from magnetic spots and flares. Where the magnetosphere anchors to the surface, accretion material from the disk is thought to funnel along columns before colliding with a shocked region where ultraviolet radiation is produced. Further out, emission lines such as H α arise from ionized gas in the accretion flow. The disk is heated by the central star, and its innermost portions ($d < 1$ AU) reradiate at near-infrared wavelengths. An inner wall may cast a shadow on the outer parts, which emit in the mid to far-infrared according to the lower dust temperatures found there. The measured flux at all of these wavelengths is further dependent on the observer’s aspect angle to the star/disk system as well as on the rotation periods of the emitting regions.

While this model involves a relatively static geometry, young stars and their disks constitute an incredibly dynamic environment, as borne out by variability studies. It has been

known for decades (e.g., Joy 1945) that young stellar objects (YSOs) display prominent optical brightness fluctuations on timescales from days to years. Light curves contain not only regular sinusoidal patterns, but abrupt and unpredictable changes as well (e.g., Cody & Hillenbrand 2010). More recently, it has become evident that many of these objects also exhibit significant variations in the near- and mid-infrared, suggestive of changes in emission from the inner disk itself (Morales-Calderón et al. 2011; Rebull 2011).

A key question is how to connect variability with the physical configuration and processes relevant to YSOs. Initial attempts to correlate the optical and near-infrared time-domain properties of young stars with models (e.g., Herbst et al. 1994; Carpenter et al. 2001) have revealed photometric behavior that is consistent with variable accretion, hot and cool photospheric spots, or variable obscuration by circumstellar material. Yet with limited wavelength coverage or temporally sparse data, these scenarios could not be distinguished unambiguously. Further work on class II sources by Eiroa et al. (2002), Bary et al. (2009), and Espaillat et al. (2011) uncovered near-IR and mid-IR flux changes implicating disk thermal and structural changes on timescales from days to years. It has been proposed that the more rapid variations reflect changes in the height of the inner disk wall (Hirose & Turner 2011; Ke et al. 2012). Additional modeling efforts such as those by Dullemond et al. (2003), Flaherty & Muzerolle (2010), and Romanova et al. (2011) have begun to offer descriptions of inner disk dynamics and star-disk interaction but require more extensive input from observations on varied timescales and wavelengths.

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Table 1 Optical and infrared space-based observations

Telescope	# of targets	Precision (mag)	Cadence (min)
<i>Spitzer</i> /map	1000	0.01–0.03	100
<i>Spitzer</i> /stare	540	0.001–0.01	0.1 or 1
CoRoT	500	0.0005–0.01	8.5
MOST	67	0.001–0.01	0.4 or 0.85

2 The Coordinated Synoptic Investigation of NGC 2264

We have embarked on an unprecedented exploration of young star variability via high-precision, simultaneous optical and infrared time series monitoring of YSOs in NGC 2264. This few-Myr-old cluster contains some 2000 known members, many of which have disks (Rebull et al. 2002; Dahm & Simon 2005). It was previously monitored in the optical (Lamm et al. 2004; Cieza & Baliber 2007) as well as a “short run” (23 days) with the CoRoT satellite (Favata et al. 2010). Results from the latter program have contributed vitally to our understanding of the complexities of YSO variability at on timescales from minutes to weeks (e.g., Alencar et al. 2010, Zwintz et al. 2011).

Our campaign—the Coordinated Synoptic Investigation of NGC 2264 (“CSI 2264”)—combines the power of precision space-based photometry with the benefits of multi-wavelength monitoring. The program commenced in early December 2011, with roughly 30 continuous days of mid-infrared photometry from *Spitzer*/IRAC and 40 continuous days of optical monitoring with CoRoT, targeting the central degree of the cluster. Four \sim 1-day blocks were dedicated to monitoring of two $5.2'$ regions near the cluster center with *Spitzer*'s high precision ($<1\%$) staring mode, whereas the remaining targets were visited in mapping mode (1–3% precision). Complementing these observations were 40 days of high-cadence, high-precision time series of 67 of the brightest cluster members with the Microvariability and Oscillations of STars telescope (*MOST*; Walker et al. 2003), as well as 350 ks (\sim 4 days) of *Chandra*/ACIS X-ray monitoring simultaneous with the *Spitzer* staring observations. In addition, synoptic ground-based optical and near-infrared data in the U through K bands was acquired simultaneously with a number of instruments, including $R \sim 17,000$ spectra from the VLT/Flames multi-object spectrograph as well as optical photometry from the USNO 40-inch telescope (I band), and the Canada-France-Hawaii Telescope MegaCam (U , R band). The bulk of this auxiliary monitoring continued through February 2012.

The space-borne instruments involved in CSI 2264 have a history of providing exquisite precision photometric time series at minute cadences (see Table 1). Since NGC 2264 is the only young open cluster available for simultaneous monitoring by *Spitzer* and CoRoT, we expect the combined dataset to provide insights into the dynamic environment of young stars and their disks for years to come. The project is still in its early stages, and we present here some initial

insights gleaned from the combination of optical and mid-infrared time series.

3 Initial results from CSI 2264

3.1 Periodic and semi-periodic variability

Periodic variability in YSOs is usually attributed to rotational modulation of the light curve by magnetic spots on the stellar surface. Many of our light curves display sinusoidal variations in both bands, and this is particularly characteristic of the type III (i.e., no infrared excess) objects that are presumed to lack disks. Typically, the IRAC amplitudes are lower than those in the optical CoRoT light curve, but the variations become more comparable toward later spectral type. A handful of objects have more than one significant period in their light curve, suggesting that spots are present at multiple latitudes, or that we are observing a binary system involving two active stars with different rotation periods. A number of eclipsing binaries also lie in the NGC 2264 field, and follow-up monitoring is expected to provide precise stellar parameters for a number of them, along with new benchmarks for comparison with models at young ages. At the bright end of the sample, asteroseismology of cluster δ Scuti stars will continue to unveil the properties of their interiors (e.g., Zwintz et al. 2011).

A subset of objects display semi-periodic variability in both bands that is not necessarily consistent with the spot modulation scenario. Much of this is large amplitude (>0.1 magnitudes) and involves a combination of repeating features as well as smaller amplitude deviations which appear and disappear on \sim 1 day timescales. We suspect that some of this behavior may be explained by the periodic passage of obscuring disk material by the face of the central star. This was the idea put forth to explain the “AA Tau” phenomenon, which was highlighted in a previous CoRoT short run dataset on NGC 2264 by Alencar et al. (2010). A prominent example of AA Tau type behavior occurs in NGC 2264 member V354 Mon, which displays \sim 0.25 magnitude fluctuations in the optical and \sim 0.06 magnitude fluctuations in the infrared. The variations in the two bands mirror each other quite well when those from the $4.5 \mu\text{m}$ band are scaled up by a factor of 4.0, as seen in Fig. 1. Supposing that the brightness variations are explained solely by changing dust extinction in the line of sight to the star, we arrive at a reddening law, $A_{4.5}/A_V$, that is approximately five times larger than the standard interstellar predictions (e.g., Indebetouw et al. 2005). Taking into account the $4.5 \mu\text{m}$ flux from the disk itself would only raise this value further. Therefore if these semi-periodic changes are indeed due to obscuration by disk material, then we can infer that its dust properties are significantly different from those of ISM grains.

In contrast, other cases of semi-periodic variability involve relatively colorless brightness fluctuations. The opacity of obscuring material may vary from star to star and play a role in determining the color trends in their light curves.

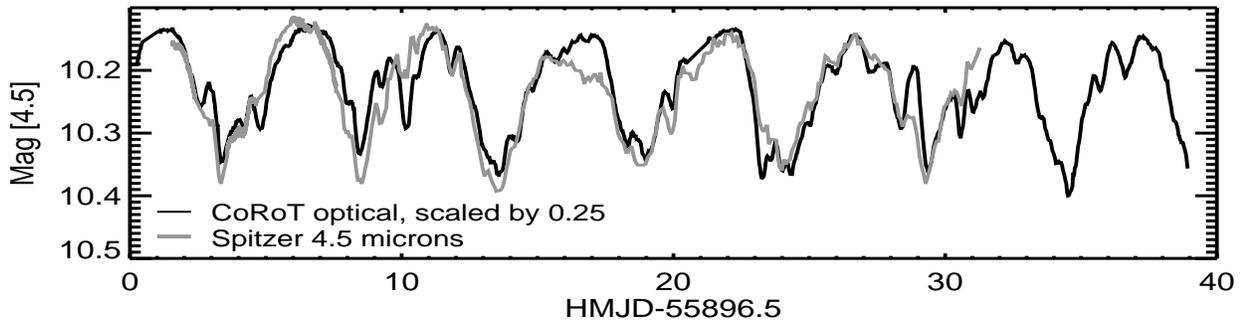


Fig. 1 The optical light curve of NGC 2264 member V354 Mon from CoRoT (black curve), with flux scaled by a factor of 0.25 and shifted so as to have the same median of the *Spitzer*/IRAC 4.5 μm data. The two light curves display variability that is well but not perfectly correlated on timescales of ~ 5 days. The scale factor is significantly different from the ratio of $A_{4.5}/A_V$ expected from an interstellar extinction law (~ 0.05).

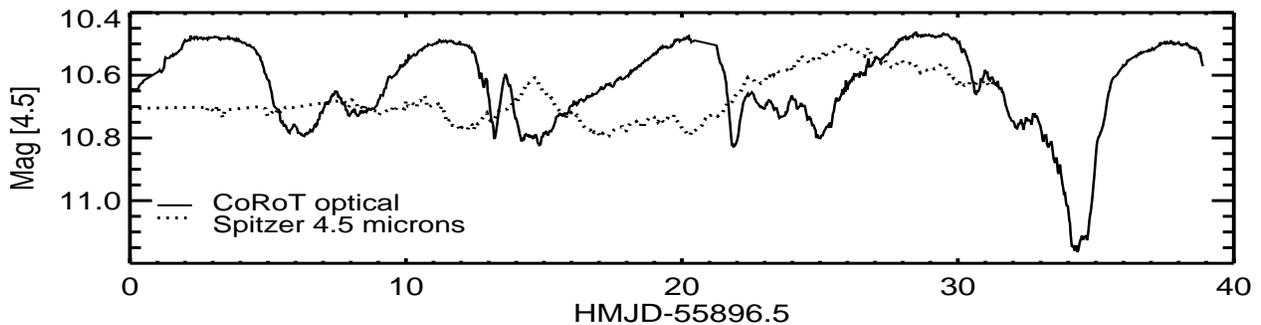


Fig. 2 An example of uncorrelated variability in optical and mid-infrared. The CoRoT data is median shifted to match the *Spitzer* zeropoint. The contrast between this behavior and the high degree of correlation in Fig. 1 might be accounted for by a different aspect angle to the disk and/or a larger fraction of the 4.5 μm luminosity coming from the inner disk, as opposed to the central star.

3.2 Aperiodic variability

The majority of disk-bearing stars in NGC 2264 display significant variability at both optical and mid-infrared wavelengths that contains aperiodic features. In most cases, the behavior in the two bands appears at least somewhat correlated. This is particularly evident for YSOs whose optical light curves display deep (>0.1 mag), semi-periodic fading events consistent with the AA Tau phenomenon. However, we also identify more extreme cases of variability, in which the brightness in both the optical and mid-infrared varies by more than 20%, but fluctuations appear completely uncorrelated at these two different bands. We present an example in Fig. 2. The largest amplitude infrared variability in these objects occurs on longer timescales (5 days or more) than that seen in the semi-periodic objects. Most of the optical light curves, on the other hand, contain high amplitude dip-like or undulating features on 1–5 day time scales.

A further subclass of variables exhibits large-amplitude variation (>0.2 magnitudes) in the IRAC bands but relatively little variation as seen by CoRoT. An example is shown in Fig. 3. The appearance of the mid-infrared light curves in

this class varies from large-amplitude excursions on 3–5 day timescales to more smoothly changing brightness on longer timescales. In cases for which fluctuations take place over several days, variability behavior evolves faster than the dynamical timescale of the inner disk. This mid-infrared flux variation may involve a combination of structural, dynamical, and thermal variations in the disk but currently lacks more detailed explanation.

Many of the cluster members monitored are accreting, based on strong $H\alpha$ emission and U -band excesses. The accretion process likely proceeds in bursts, and changes in accretion luminosity may be another source of stochastic variability in YSOs. We tentatively identify a number of cases for which the optical brightness undergoes abrupt brightening events consistent with accretion changes. Flux outbursts typically last several days, with lower level structure on shorter timescales. Nearly all of these objects display significant UV excesses, as inferred from our CFHT/Megacam U -band dataset. Figure 4 illustrates an example of behavior that we attribute to accretion. Where IRAC photometry is available and unsaturated, the mid-infrared flux typically

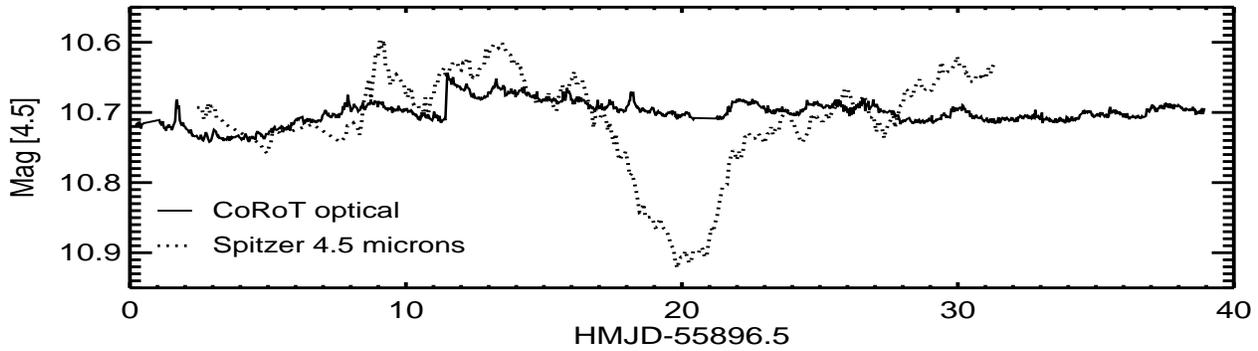


Fig. 3 An example in which mid-infrared variability appears with large amplitude, whereas optical brightness fluctuations occur at a much lower level.

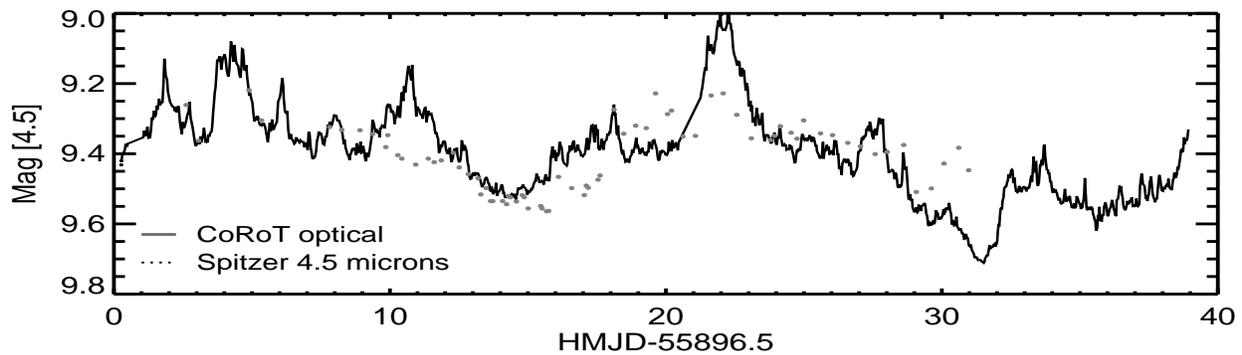


Fig. 4 NGC 2264 member for which abrupt increases in optical brightness are suggestive of accretion bursts.

displays similar abrupt increases, probably reflective of disk heating following an increase in accretion luminosity.

4 Summary

The CSI 2264 project offers great potential to unlock the multiwavelength time-domain properties of YSOs across a range of stellar and disk properties. Further investigation of this high-precision, high-cadence dataset is expected to shed light on the physical mechanisms of variability and potentially reveal the properties of otherwise inaccessible inner disk regions. The eventual inclusion of high-resolution spectroscopic data for a subset of targets, as well as photometry at other bands from the X-ray through near-infrared, will enhance these efforts. Ultimately, reduced data from the campaign will be made publicly available from a website hosted at the NASA/Caltech Infrared Processing and Analysis Center.

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