Rotation and Spitzer/IRAC fluxes in Orion

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(including work done with S. Wolff, S. Strom, S. Ramirez, & E. Flaccomio)

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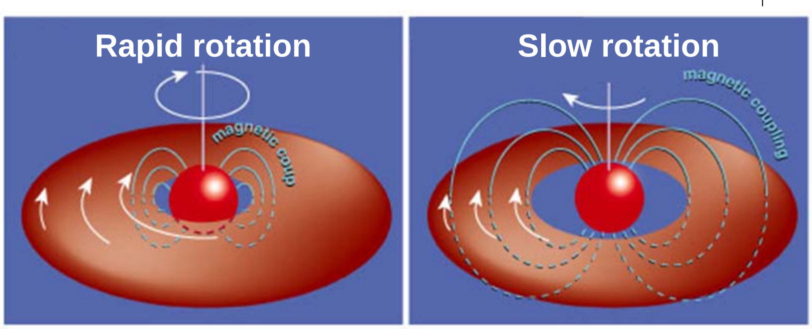
Outline

- Brief summary of the problem (or, rather, the confusion).
- Spitzer/IRAC fluxes for stars in Orion with rotation periods.
- If there is time, Chandra fluxes for stars in Orion (and NGC 2264) with rotation periods, and comparison to IRAC fluxes.

The Goal

- Do disks regulate the rotation rates of young, low mass stars? When does the influence of the disk start/stop? (Regulation may not be locking, and regulation timescales may not be the same as influence timescales.)
- We need a multi-wavelength approach to this problem because it has many different facets (star/disk system physics, orientation).

Disk Locking Along Birthline (Königl Model)



High [dM_{acc}/dt] or weak **B** Low [dM_{acc}/dt] or strong **B**

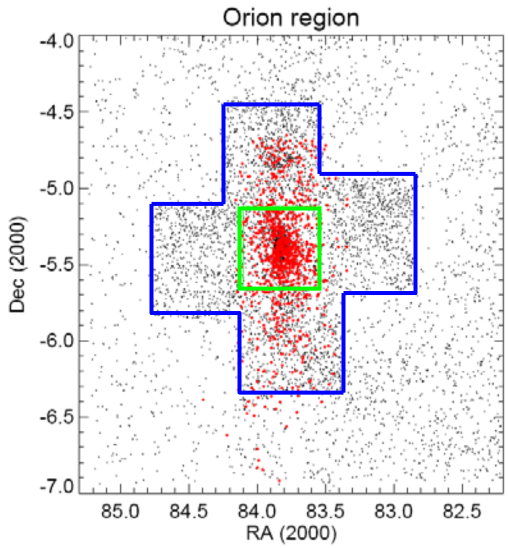
$$\Omega \sim \varepsilon\, GM^{5/7} (dM_{acc}/dt)^{3/7} B^{-6/7} R^{-18/7}$$

Shu+Najita model invokes wind to carry away stellar angular momentum.

The dependence of Ω on B, dM_{acc}/dt and R is similar

Where are we in space?

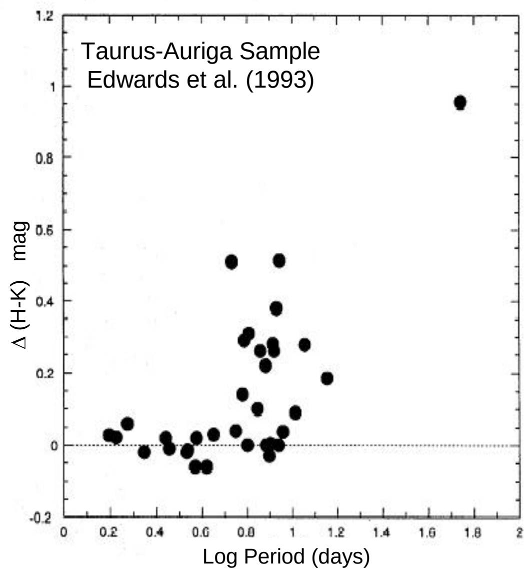
Stars with rotation information *and* IRAC fluxes



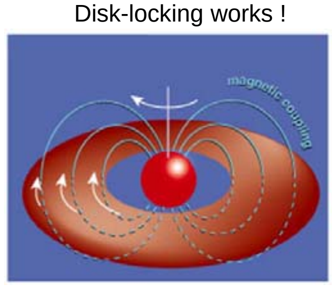
Orion Flanking Fields (FF) (Rebull et al.)

"Traditional" ONC region (Hillenbrand et al., Herbst et al., Getman et al.…)

What Regulates Stellar Angular Momenta?



Disk-locking works !



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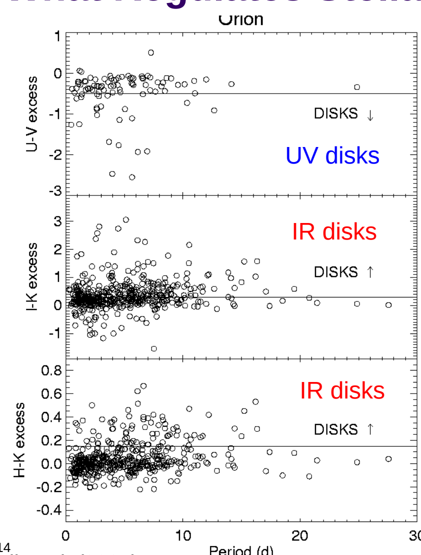

Rebull et al. (2001)

Disk-locking fails !

Confusing!

Simple Regulation Predictions

- If the star is regulated (stellar angular velocity conserved), then as the stars contract, they rotate at the same rate.
- If stellar Ω(~v/R) is conserved, then P ~ constant (independent of R), or v ~ R.
- If stellar angular momentum is conserved, as the stars contract, they spin up.
- If stellar J (~ MvR) is conserved, then P ~ R^2, or v ~ 1/R.
- (R is obtained from a dereddened HRD)

Rotation in young clusters

- We obtained from the literature P or v sin i, V, I, and spectral types for >1000 stars in Orion, TW Hya, Cha, ρ Oph, NGC 2264, Tau-Aur, Lupus, and η Cha.
- Limited to types K5-M2 (effectively a cut in mass) to limit mass and age effects.
- P and v sin i data are two ***independent*** measures of rotation in these stars.

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Rebull et al. (2004)

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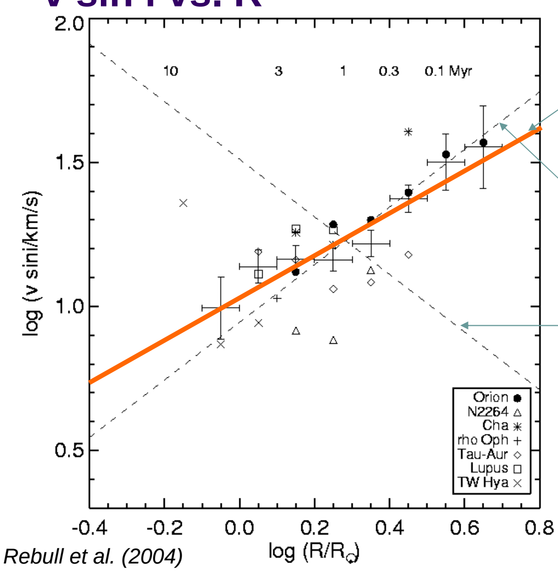
Mapping Angular Momentum Evolution: v sin i vs. R



Best Fit

Stellar Ω conserved: v ~ R

Stellar J conserved: v ~ R^{-1}

Rebull et al. (2004)

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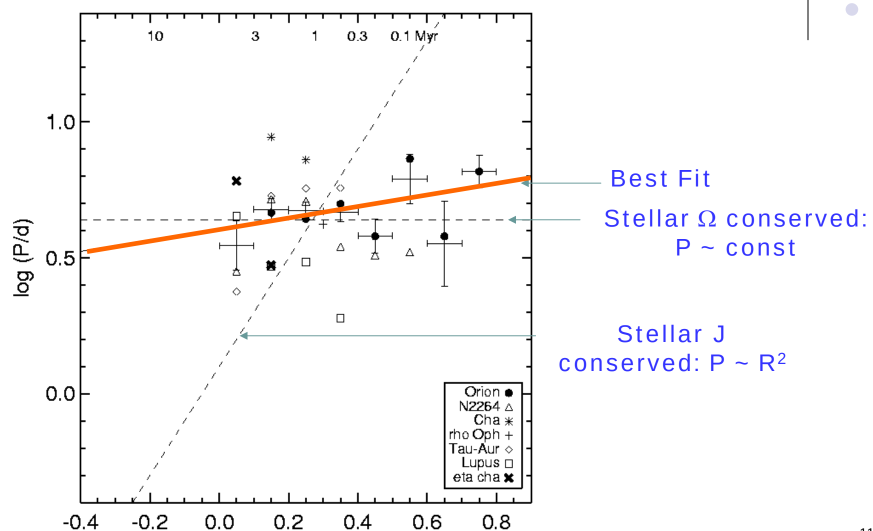
Mapping Angular Momentum Evolution: P vs. R



Rebull et al. (2004)

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SOMETHING is regulating the stellar angular momenta!

- The angular momenta of a significant fraction of PMS stars with ages <5 Myr must be tightly regulated since <P>~const and <v>~R.
- BUT there does not seem to be a difference between stars with and without I-K excesses!
- (Note that there is a gap near 10 Myr; it is important to find clusters to fill this gap and find out how this distribution maps into Pleiades and later.)

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For much more discussion, see Rebull et al. 2002, 2004

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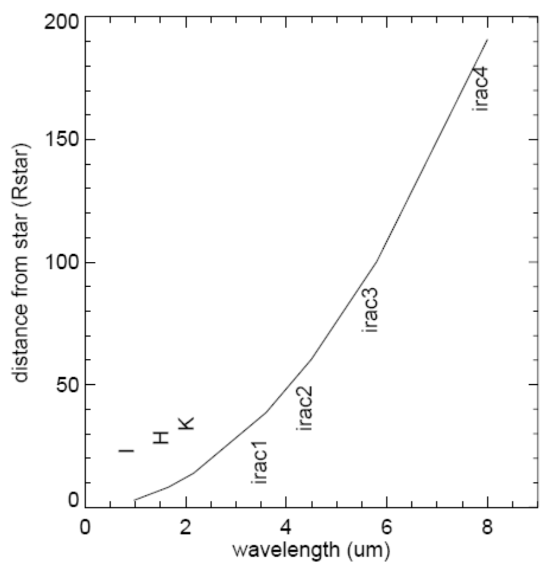
Why is the evidence for disk regulation ambiguous?

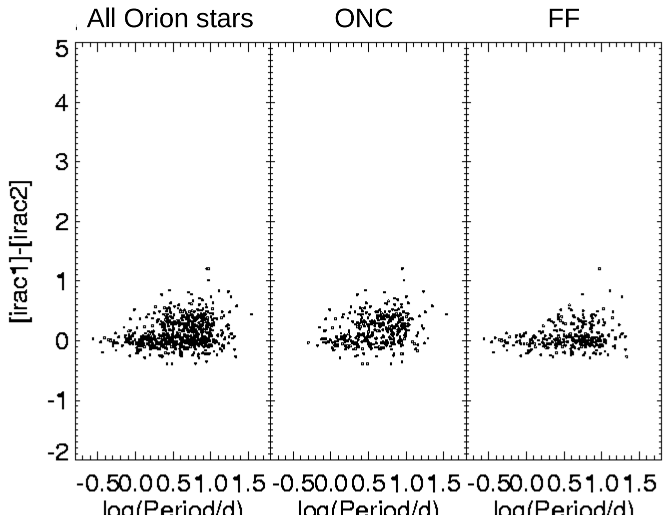
- Sample sizes are not large enough to distinguish period distributions for (disk-) regulated and unregulated stars. *e.g. Rebull et al. 2004*
  - N(P) spans a factor of 10.
  - Subtle (and even not so subtle) differences can be masked even with sample sizes of several hundred stars.
- Near-IR excesses cannot identify disks with 100% certainty – inner disk holes and inclination effects can be confusing. *e.g. Hillenbrand et al 1998*

Astro 101 version of distance from star & peak emission wavelength



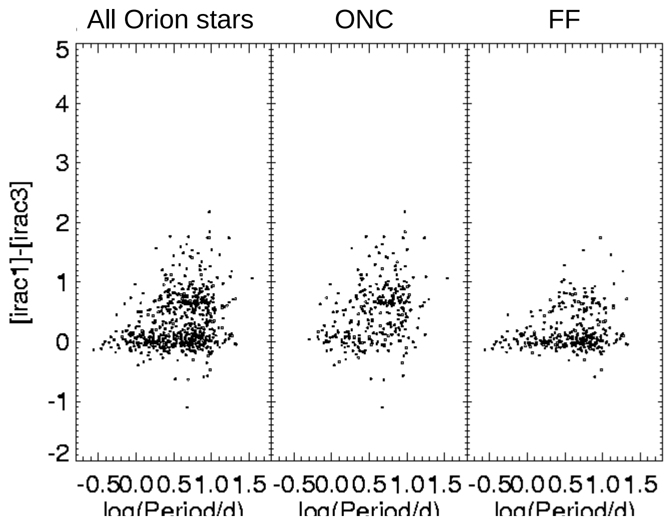
(Parameters used are for a typical star in the sample.)
IRAC fluxes are sensitive to disks at much larger radii than NIR fluxes.
(In reality, it is not even remotely this simple, and is subject to heated inner walls/ rims, system inclination, disk-photosphere contrast, etc.)

[IRAC 1] – [IRAC 2]



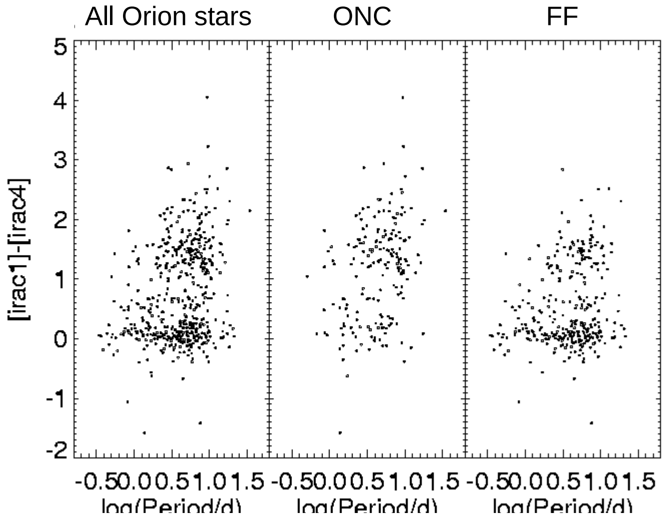
Using a 2-D KS test, the ONC distribution is *significantly* different than the FF distribution!

[IRAC 1] – [IRAC 3]



Using a 2-D KS test, the ONC distribution is *significantly* different than the FF distribution!

[IRAC 1] – [IRAC 4]



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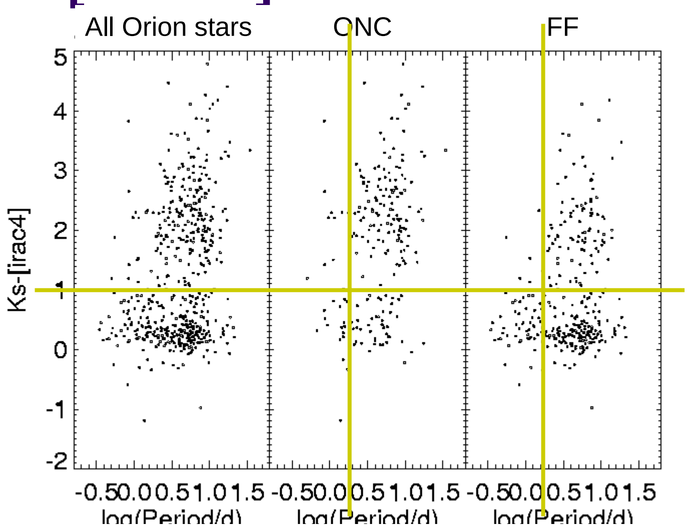
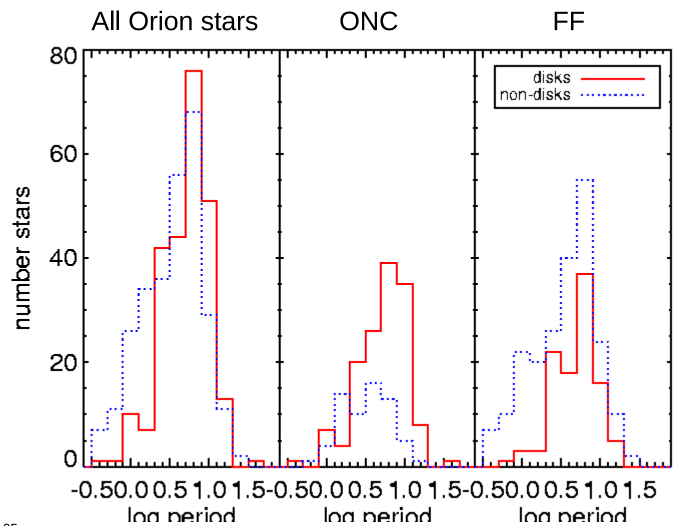
Ks – [IRAC 4]



Using a 2-D KS test, the ONC distribution is *significantly* different than the FF distribution! (But is it the periods or the IR fluxes which are different?)

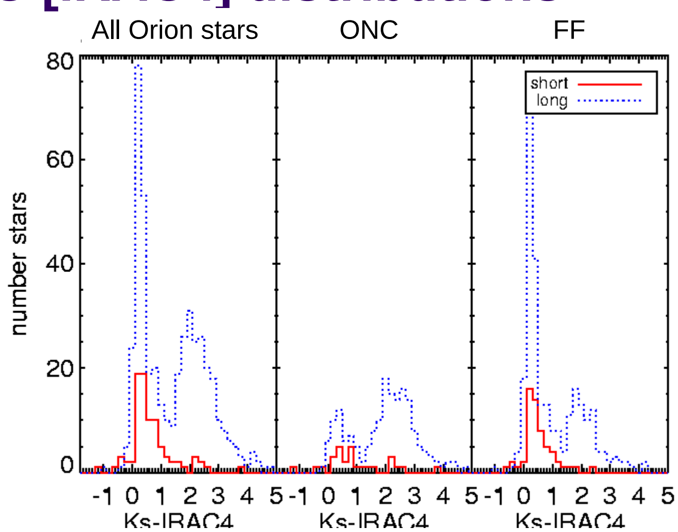
P distributions



(Disk candidates are those with Ks-[IRAC4] > 1.)

Using a 1-D KS test, the P distributions are similar. *Weak* evidence for *slightly* longer period among disk candidates.

Ks-[IRAC4] distributions

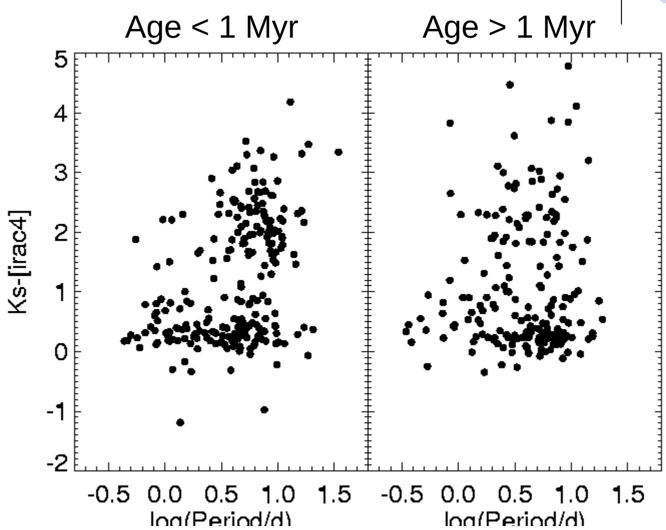


Using a 1-D KS test, the distributions of Ks-IRAC4 for periods > and < 1.8 d are *very* different! *=> Excesses don't necessarily imply longer periods, but longer P more likely than shorter P to have excesses!*

Age (and Mass) effects?

KS test says two populations probably come from the same parent distribution – more scatter in the older stars?

No significant mass effects found.



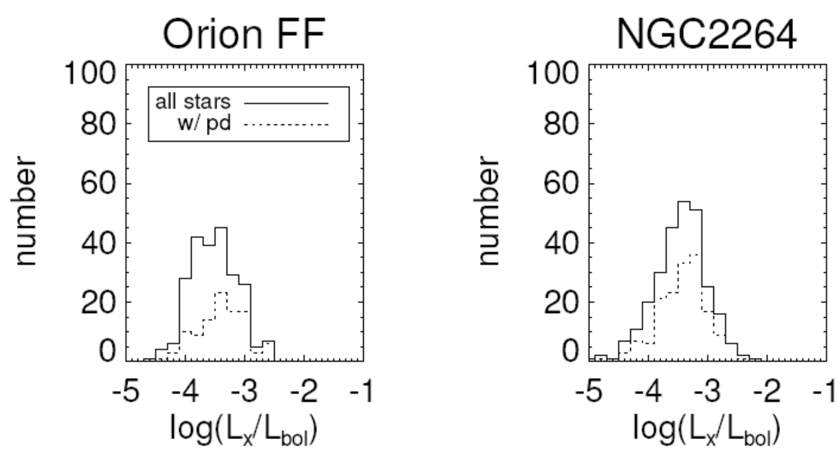
Remarks on IRAC results

- As we move to longer wavelengths, the population separation between disked/non-disked becomes more dramatic.
- Excesses don't necessarily imply long periods, but long periods seem more likely than short periods to have excesses!
- Disks may very well still be influencing these stars. Something has to be regulating the stars, and it was disturbing (at least to me) that we weren't finding clear correlations with other NIR (and UV) disk indicators.
- What does this mean for the gas density in the inner disk? Does a correlation with IRAC but not NIR excesses imply large inner dust disk holes, or is this all inclination effects? What does this mean for disk locking?
- Is the timescale for disk clearing comparable to other important timescales here? Were they locked with closer-in disks, only recently having cleared out to IRAC radii, but still behaving as disk-locked? Could we be having disk *braking* without disk *locking*?

Folding in Chandra

- Rotation is clearly related to X-ray flux in older stars (e.g., Pleiades), and there should be a point at which this relationship “turns on” for YSOs. Rotation seems to be connected to disks as well, so we can investigate correlations between Spitzer and Chandra.
- Chandra data were obtained for two fields in Orion FF and two fields in NGC 2264.
(Ramirez et al., 2004a, b; Flaccomio et al. 2005)
- Not anywhere as deep as COUP, of course, but samples older stars on average than ONC.

Stars that have measured periods are brighter in X-rays



Rebull et al. in prep

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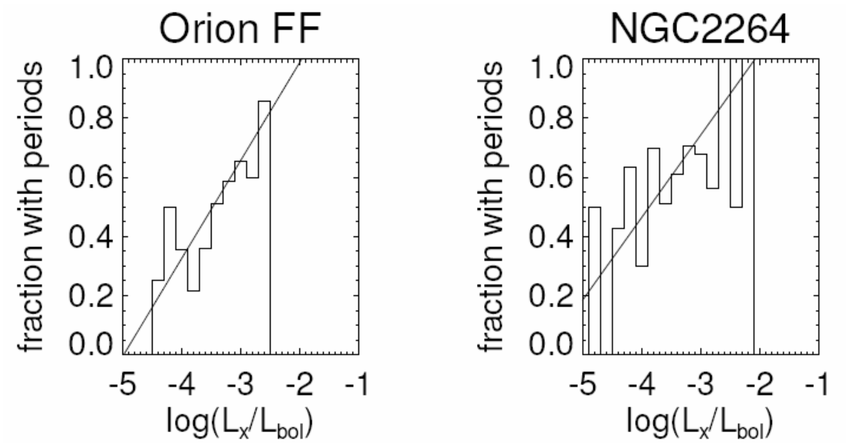

Bias is also found in ONC by Flaccomio et al. 2003 and Stassun et al 2004.

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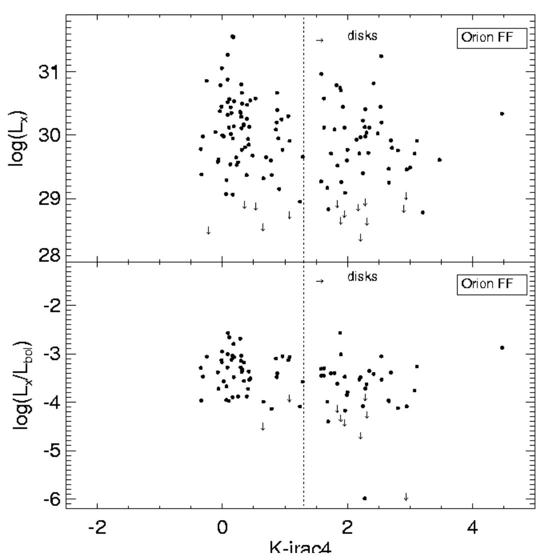
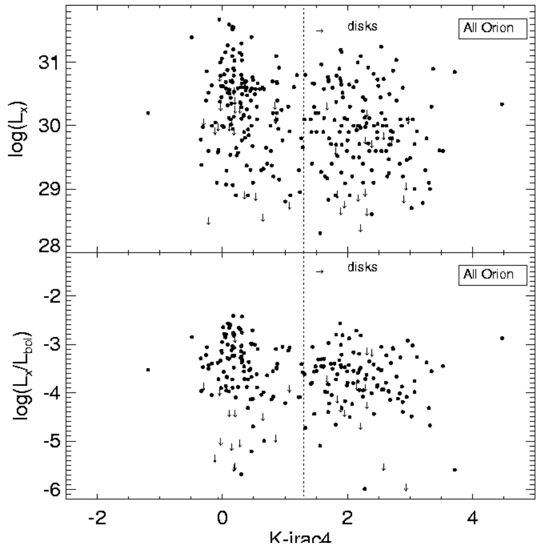
Ks – [IRAC 4] vs. X-rays in FF



ALL STARS here have measured periods. *Weak* evidence for lower Lx and Lx/Lbol in disk candidates.

Ks–[IRAC 4] vs. X-rays in all of Orion



ALL STARS here have measured periods. *Weak* evidence for lower Lx and Lx/Lbol in disk candidates. (COUP says that this may indicate disruption of the dynamo by accretion onto convective envelope.)

Remarks on Spitzer+Chandra results

- There is a clear bias in that stars with measured periods are brighter in X-rays.
- There is very weak evidence that stars with periods and IRAC excesses are brighter in X-rays than stars with periods and no IRAC excesses.

Concluding thoughts

- IRAC excesses don't necessarily imply long periods, but long periods are more likely than short periods to have IRAC excesses! Disks seem to still be influencing these stars.
- Is the timescale for disk clearing comparable to other important timescales here? Were they locked with closer-in disks, only recently having cleared out to IRAC radii, but still behaving as disk-locked? Could we be having disk *braking* without disk *locking*?
- Stars with measured periods are clearly brighter in X-rays.
- Still need more stars, and more clusters near 10 Myr, to answer the original questions: Do disks regulate the rotation rates of young, low mass stars? When does the influence of the disk start/stop? (NGC 7160, Sco-Cen are of the right age…)