OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **Proposal type:** short-term

Magnetic Fields of Low-Mass Young Stars in the β Pictoris Moving Group

P.I.: Hao Yang (SO; *haoyang@email.arizona.edu*; 520-621-0359)

CoI(s): Christopher Johns-Krull (Rice University), Don McCarthy (SO), Craig Kulsea (SO)

Abstract of Scientific Justification

We proposal to use ARIES on MMT to obtain high-resolution K-band spectra for a sample of low-mass young stars in the β Pictoris Moving Group (12–23 Myr). We will model the Zeeman broadening in the Ti I lines in these data and measure the magnetic fields on these stars. The measurements will extend our understanding of magnetic properties of young stars beyond 10 Myr, and allow us to test turbulent and interface dynamo models, and particularly the possible primordial origin of magnetic fields on the young stars and the potential transition from primordial fields to dynamo-generated fields.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/15	ARIES	*	*	1.0	bright	Jan–Feb	Jan–Mar	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: None

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a * appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	GJ 2006A	00:27:50.23	-32:33:06.4	M4Ve, V=12.87, K=8.01, $v\sin i$=4.0 km s^{-1}
2	HIP 11152	02:23:26.63	$+22$:44:06.9	M3Ve, V=11.32, K=7.35, $v\sin i$= 6.0 km s^{-1}
3	HIP 11437A	02:27:29.24	$+30$:58:24.6	K7, V=10.12, R=9.32, K=7.08, $v\sin i$= 5.0 km s^{-1}
4	HIP 11437B	02:27:28.05	$+30$:58:40.5	M0, V=12.55, K=7.92, $v\sin i$= 5.0 km s^{-1}
5	V962 Per	04:43:56.86	$+37$:23:03.3	M3Ve, V=12.98, R=12.75, K=7.08, $v\sin i$= 5.0 km s^{-1}
6	GJ 3322A	05:01:58.79	$+09$:58:59.3	M3V, V=11.52, R=11.80, K=6.37, $v\sin i$= 7.7 km s^{-1}
7	2MASS J05335981-0221325	05:33:59.81	-02:21:32.5	M3Ve, V=12.42, K=7.70, $v\sin i$= 5.4 km s^{-1}

Approval for Instrument Use from PI: See attached e-mail from Don McCarthy.

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Magnetic fields are believed to play a fundamental role throughout the star and planet formation process, especially with regard to the interaction between a young star and its circumstellar proto-planetary disk. Stellar magnetic fields are thought to truncate the disk near the corotation radius, directing the flow of accreting material toward the polar regions of the central star (Camenzind 1990; Königl 1991; Cameron & Campbell 1993; Shu et al. 1994, Paatz & Camenzind 1996). The radius at which the stellar field truncates the inner disk may determine the final orbit of inward migrating planets (Lin et al. 1996; Eisner et al. 2005). Stellar fields probably also play a critical role in driving the strong winds/jets seen in young stars. These interactions determine the angular momentum evolution of the star and disk, likely setting the time scale for disk dissipation and planet building. Stellar activity affects the thermal and chemical structure in the disks (Kamp & Dullemond 2004), which in turn affects the planet building process. Understanding of the early evolution of stars and their disks requires detailed exploration of the stellar magnetic field properties.

Model predictions show that young stars should possess a wide range of magnetic field strengths, with surface averaged magnetic field values ranging from a few hundred Gauss up to $>$ 4 kG for some stars (Johns-Krull et al. 1999; Cauley et al. 2013). Within the past decade or so, by modeling the Zeeman broadening in the magnetically sensitive Ti I lines (Figure 1), fields of this magnitude have been detected on a few dozen T Tauri stars (TTSs, Johns-Krull et al. 1999, 2001, 2004, 2007; Valenti & Johns-Krull 2004; Yang et al. 2005, 2008; Yang & Johns-Krull 2011), providing strong support for magnetospheric accretion theories.

However, many open questions remain. With the limited magnetic field data currently in hand, there is no correlation between the measured and predicted field strengths (Bouvier et al. 2006; Johns-Krull 2007; Yang & Johns-Krull 2011). Current field strengths also present a challenge for modern dynamo theories. Young stars are relatively rapid rotators compared to solar-age main-sequence stars, and are therefore expected to have enhanced dynamo activity. However, the solar dynamo is believed to operate in the overshoot region at the base of the Sun's outer convection zone. The late type TTSs that have been studied to date are generally fully convective, and thus are incapable of utilizing such a dynamo. It is believed that turbulent dynamos (e.g., Durney, DeYoung, & Roxburgh 1993) are not capable of producing large scale $\sim$ 2.5 kG fields as observed. If such fields are indeed a general feature on TTSs, the efficiency of turbulent dynamo models will have to be re-explored, or a primordial origin for these strong stellar fields will have to be considered. Little work has been done on the dissipation time scale for primordial magnetic fields that might be entrained from the interstellar medium during the star formation process. The few estimates that are available (Tayler 1987, Moss 2003) suggest that such a field could last as long as a few Myr. Therefore, we might expect to see a decay of the magnetic field strength with time over the first few Myr.

Yang et al. (2011) reported magnetic field measurements of 14 TTSs in the Orion Nebula Cluster (ONC) and compared the magnetic properties of stars in three different regions: the ONC ($\sim$ 1 Myr), Taurus ($\sim$ 2 Myr), and the TW Hydrae Association (TWA, $\sim$ 10 Myr). They found that the measured magnetic flux displays a systematic decrease from the younger ONC stars to the older TWA stars (Figure 2), lending support to a primordial origin of magnetic fields on TTSs. The measured fields/fluxes also do not correlate with any other expected dynamo properties such as rotation period and convective turnover time. On the other hand, the field strengths do not show any systematic change over age. It is unclear whether the fields measured on these stars younger than 10 Myr are generated by a stellar dynamo or of primordial origin. At a certain pre-main sequence evolutionary stage, dynamo-generated fields are expected to become dominant when primordial magnetic fluxes decay. When and how this happens is still pending investigation.

Currently, little is known about the actual magnetic fields of low-mass stars over 10 Myr old, so observations are required to determine how magnetic properties of these stars evolve. Around 12–23 Myr old (Zuckerman et al. 2001; Mamajek et al. 2014), the stars in the nearby β Pictoris Moving Group (βPMG) are ideal candidates for this study. We propose to observe 7 stars in the βPMG as a first step to explore the magnetic fields of low-mass stars older than 10 Myr. Such measurements will provide a fuller picture of the temporal evolution of magnetic properties of pre-main sequnce stars.

References

Allard, F. & Hauschildt, P. H. 1995, in Bottom of the Main Sequence and Beyond (Berlin: Springer), 32
Bouvier, J. et al. 2007, Protostars and Planets V (University of Arizona Press, Tucson), 479
Camenzind, M. 1990, Rev. Modern Astron. (Berlin: Springer-Verlag), 3, 234
Cameron, A. C. & Campbell, C. G. 1993, A&A, 274, 309
Cauley, P. W., Johns-Krull, C. M., Hamilton, C. M., & Lockhart, K. 2012, ApJ , 756, 68
Durney, B.R., De Young, D.S., & Roxburgh, I.W. 1993, Sol. Phys., 145, 207
Eisner, J. A., Hillenbrand, L. A., White, R. J., Akeson, R. L., & Sargent, A. I. 2005, ApJ , 623, 952
Johns-Krull, C., Valenti, J., & Koresko, C. 1999, ApJ , 516, 900
Johns-Krull, C.M., Valenti, J.A., Saar, S.H., & Hatzes, A.P. 2001, Proceedings of 11th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun; ASP Conf. Ser., Vol. 223, 521
Johns-Krull, C. M., Valenti, J. A., & Saar, S. H. 2004, ApJ , 617, 1204
Johns-Krull, C. M. 2007, ApJ , 664, 975
Kamp, I., & Dullemond, C. P. 2004, ApJ , 615, 991
Konigl, A. 1991, ApJ , 370, L39
Lamm, M. H., Mundt, R., Bailer-Jones, C. A. L., & Herbst, W., 2005, A&A, 430, 1005
Lin, D.N.C., Bodenheimer, P., & Richardson, D.C. 1996, Nature, 380, 606
Mamajek, E. E., & Bell, C. P. M. 2014, MNRAS , in press (arXiv:1409.2737)
Moss, D. 2003, A&A, 403, 693
Paatz, G. & Camenzind, M. 1996, A&A, 308, 77
Shu, F. H., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, ApJ , 429, 781
Tayler, R.J. 1987, MNRAS , 227, 553
Valenti, J. A., & Marcy, G. W., & Basri, G. 1995,ApJ , 439, 939
Valenti, J. A., & Johns-Krull, C. M. 2004, Ap&SS , 292, 619
Yang, H., Johns-Krull, C.M., & Valenti, J.A. 2005, ApJ , 635, 466
Yang, H., Johns-Krull, C.M., & Valenti, J.A. 2008, AJ , 136, 2286
Yang, H. & Johns-Krull, C.M. 2011, ApJ , 729, 83
Zuckerman B., Song I., Bessell M. S., & Webb R. A. 2001, ApJ , 562, 87

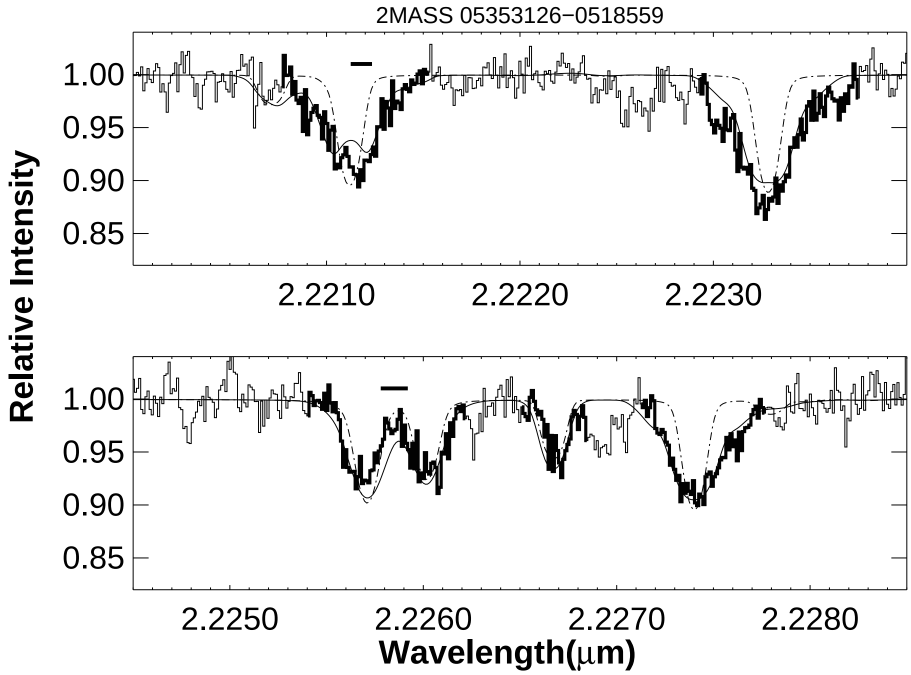

Figure 1: K-band spectra of 2MASS 05353126-0518559 in the Orion Nebular Cluster observed with Phoenix on Gemini South (from Yang & Johns-Krull 2011). The histogram shows the data with three magnetically sensitive Ti I lines at 2.2211, 2.2232, and 2.2274 μm. Two Fe II lines at 2.2257 and 2.2260 μm and one Sc I line at 2.2267 μm have weak magnetic sensitivity. The dash-dotted line is a synthetic spectrum with no magnetic field, and the smooth solid line is the best fitting model with a mean magnetic field of 2.8 kG. The spectral regions in bold are used in the fit. The solid horizontal bars mark the wavelengths where telluric absorption is stronger than 3% of the continuum.

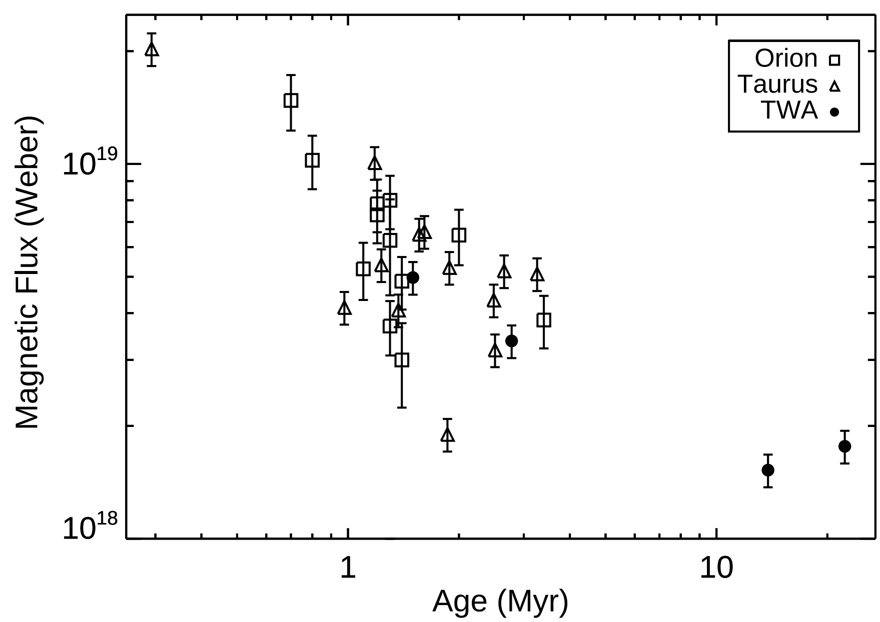

Figure 2: Magnetic flux shows a decreasing trend with age in the first 10 Myr of pre-main sequence evolution. (from Yang & Johns-Krull 2011).

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

In order to explore the evolution of magnetic fields beyond 10 Myr, we propose to obtain high-resolution ($R \sim$ 50,000) K-band spectra of 7 late-K and early-M stars in the βPMG using ARIES on MMT. For these cool stars, there are several Ti I lines in the K-band (Figure 1) that are excellent diagnostics of magnetic fields. We will model the Zeeman broadening in the magnetically sensitive Ti I lines and measure the field strengths on these late-type stars. The spectra also cover numerous atomic or molecular features that are of weak or no magnetic sensitivity, such as the Fe II and Sc I lines shown in Figure 1, and some CO lines near 2.310 μm. These spectral features will help us constrain stellar parameters such as $T_{\rm eff}$, log g, and $v \sin i$, making sure that our models predict accurately the line profiles with no magnetic field and properly take into account all the non-magnetic line broadening mechanisms (mostly thermal, turbulent, and rotational). We have also shown that small errors in stellar parameters only introduce a 10% error in magnetic field measurements (Yang et al. 2005). We will analyze our spectra with a sophisticated radiative transfer code which models all four Stokes parameters simultaneously and includes a full molecular equation of state (Valenti et al. 1995). By modeling excess line broadening due to magnetic fields, we determine the stellar magnetic field strength.

As our method is most sensitive on stars with relatively low $v \sin i$, we have selected all our targets to have $v \sin i < 8$ km s^{-1}. Zeeman splitting is proportional to λ^2 and the best K-band diagnostic splits by 18 km s^{-1} kG^{-1}. With the 6 km s^{-1} resolution provided by the echelle grating of ARIES, we can achieve a detection limit of $\sim$ 300 G.

Our targets all have V$<$ 13.5, good for AO natural guide star observing. According to the ARIES Wiki, in $R \sim$ 50,000 mode ARIES can achieve a S/N of 10 in one hour of total integration for a point souce of K$\sim$ 12. The K magnitudes of our targets are all around 8 or brighter. For each target, we plan to take one hour of exposure, which should achieve a S/N of $\sim$ 50 for the K$\sim$ 8 targets and $\sim$ 100 for the K$\sim$ 7 or brighter targets. Taking into account the overhead for setting up AO at the beginning of the night (30 mins) and target acquisition (15 mins each), plus oberving telluric standards for airmass correction, the total observing time comes to around 10 hours, and we request one night for this project.

$\boxed{\textbf{Summary of Time Requested and Awarded}}$ *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

We are requesting one UAO night for this project for the 2015A semester. No UAO or non-UAO observing time has been previously allocated.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

I have not used the facilities available through UAO in the past.

Re: ARIES
Don McCarthy [dwmccarthy@gmail.com]
Sent: Wednesday, October 01, 2014 11:07 AM
To: Yang, Hao - (haoyang)
Cc: Craig Kulesa [ckulesa@as.arizona.edu]

Hello Hao,

We are happy to collaborate in your use of ARIES!

Please note that we cannot provide ARIES during June and July.

Don

On Wed, Oct 1, 2014 at 2:09 AM, Yang, Hao - (haoyang) <haoyang@email.arizona.edu> wrote:

> Hi Don and Craig,
>
> Please see attached the current draft. Your comments and email of approval
> will be greatly appreciated! :-)
>
> Thanks,
> Hao
>
> _______________________________
> Dr. Hao Yang
> Postdoctoral Research Associate
> Steward Observatory
> University of Arizona
> Phone: (520)621-0359
> Email: haoyang@email.arizona.edu
>
> ---
>
> **From:** Yang, Hao - (haoyang)
> **Sent:** Tuesday, September 30, 2014 12:32 AM
>
> **To:** Don McCarthy; ckulesa@as.arizona.edu
> **Subject:** RE: ARIES
>
> Hi Don and Craig,
>
> Please find attached a crude draft of the proposal. I will appreciate your comments on it, especially
> regarding the targets. I'm still trying to add a few more.
>
> Thanks,
> Hao
>
> _______________________________
> Dr. Hao Yang
> Postdoctoral Research Associate
> Steward Observatory
> University of Arizona
> Phone: (520)621-0359
> Email: haoyang@email.arizona.edu
>
> ---
>
> **From:** Yang, Hao - (haoyang)
> **Sent:** Monday, September 29, 2014 5:15 PM
> **To:** Don McCarthy; ckulesa@as.arizona.edu