OBSERVING REQUEST
University of Arizona Observatories

Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term

Searching for the bottom of the IMF in Taurus

P.I.: Taran Esplin (SO; *taran.esplin@gmail.com*; 503 883 3729)
CoI(s): Kevin Luhman (PSU)

Abstract of Scientific Justification

The measurement of the minimum mass of the IMF would provide a fundamental test of theories of star and planet formation. To provide better constraints on the shape of the substellar IMF and its minimum mass, we have identified candidate low-mass stars and brown dwarfs in the Taurus star-forming region (140 pc) using optical/IR color-magnitude diagrams and proper motions measured primarily with IRAC on *Spitzer* and UKIDSS. We have obtained near-IR spectra of 26 candidates with Gemini and IRTF to measure their spectral types and determine if they are members of Taurus. 58% of those candidates were confirmed as members with masses as low as 5 $M_{\rm Jup}$. We propose to obtain spectra of the remaining 39 candidates with the Red Channel Spectrograph and MMIRS. We also propose to obtain WFCAM images of the Taurus aggregates that lack observations in some of the UKIDSS filters, which will allow us to extend our search to those areas.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	UKIRT		WFCAM			1	bright	Nov–Dec	Oct–Dec	yes	yes
2	MMT		MMIRS	*		1	bright	Nov-Dec	Oct–Dec	yes	yes
3	MMT		Red			1	bright	Nov-Dec	Oct–Dec	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: To keep the targets at least 10° from the moon, we cannot observe on: 9 – 10 October, 4 – 5 November, and 2 – 3 December.

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	Taurus	04:30:00.00	+25:00:00.0	Star-forming Region – WFCAM
2	T2919196	04:28:58.59	+15:17:38.6	i=15.8, K=12.1 – Red
3	T2897168	04:45:12.73	+30:28:03.9	i=16.1, K=12.3 – Red
4	T185708	04:00:27.89	+20:31:59.0	i=16.1, K=12.2 – Red
5	T1243911	04:48:21.76	+29:28:05.0	i=16.3, K=12.1 – Red
6	T2917679	04:38:17.54	+15:58:36.0	i=16.3, K=12.5 – Red
7	T2070755	05:00:43.35	+18:47:13.3	i=16.6, K=12.7 – Red
8	T160879	04:20:49.33	+21:15:07.3	i=17.0, K=12.5 – Red
9	T2964937	05:00:02.85	+18:28:48.5	i=17.1, K=13.0 – Red
10	T2811977	04:23:32.91	+19:50:19.3	i=18.0, K=12.6 – Red
11	T2888414	05:09:59.08	+30:36:45.4	i=18.0, K=13.2 – Red
12	T2815965	04:00:54.83	+21:17:21.1	i=18.3, K=13.7 – Red
13	T600617	04:28:59.66	+24:25:49.4	i=19.9, K=14.6 – Red
14	T2962068	04:44:38.39	+17:00:01.5	i=20.2, K=14.6 – MMIRS
15	T2850537	04:29:05.11	+27:05:56.3	i=20.2, K=14.4 – MMIRS
16	T2986996	04:46:46.75	+21:37:39.5	i=20.7, K=15.0 – MMIRS
17	T2904736	04:11:37.56	+28:28:55.0	i=21.0, K=15.3 – MMIRS
18	T2904737	04:11:31.02	+28:29:33.8	i=21.1, K=15.4 – MMIRS
19	T4962119	04:41:51.20	+25:27:36.3	i=21.7, K=15.8 – MMIRS
20	T4923088	04:41:10.54	+25:18:41.7	i=21.9, K=15.8 – MMIRS
21	T4839699	04:41:25.81	+24:59:03.9	i=21.9, K=15.8 – MMIRS
22	T2981609	04:36:42.68	+19:01:35.2	i=22.0, K=14.8 – MMIRS
23	T4681536	05:04:18.06	+24:23:02.3	i=22.4, K=15.7 – MMIRS
24	T7462337	04:24:48.09	+27:36:33.9	i=23.4, K=16.4 – MMIRS
25	T7409841	04:39:06.48	+25:29:27.5	i=23.5, K=16.4 – MMIRS
26	T7425897	04:41:08.33	+25:22:29.6	i=24.8, K=16.0 – MMIRS

Approval for Instrument Use from PI: See attached e-mall from Brian McLeod

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

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

Scientific Justification

Several mechanisms have been proposed for shaping the initial mass function (IMF) of low-mass stars and brown dwarfs, which include 1) gravitational compression and fragmentation of gas in a massive collapsing core (Bonnell et al. 2008), 2) dynamical interactions among protostars in a massive core (Reipurth & Clarke 2001; Bate et al. 2002), 3) photoionizing radiation from OB stars (Hester et al. 1996; Whitworth & Zinnecker 2004), and 4) turbulent compression and fragmentation of gas in a molecular cloud (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008). These theories predict minimum masses of the IMF that range from 0.001 to 0.1 $M_\odot$ (1–100 $M_{\rm Jup}$, Low & Lynden-Bell 1976; Larson 1992; Whitworth et al. 2007, references therein). Thus, measurements of the minimum mass of the IMF and its dependence on star-forming conditions would provide fundamental tests of theories of star formation.

Surveys for brown dwarfs have been performed primarily in the solar neighborhood ($<$ 30 pc) and the nearest star-forming regions and open clusters (150-300 pc). Those surveys have uncovered brown dwarfs with masses down to $\sim$5–10 $M_{\rm Jup}$ (Kirkpatrick et et al. 2012; Luhman 2012). The resulting IMFs show no indication of a low-mass cut-off down to their completeness limits (typically 10–30 $M_{\rm Jup}$), and they tend to suffer from poor number statistics at the lowest masses. As a result, more sensitive observations are required to identify the least massive brown dwarfs. To detect brown dwarfs at < 10 $M_{\rm Jup}$ in relatively large numbers, the nearest star-forming regions and young associations ($<$ 10 Myr) are the most promising hunting grounds given the sensitivities of existing telescopes. For instance, a 2 $M_{\rm Jup}$ brown dwarf in a nearby star-forming region should have $K \sim 20$ (Burrows et al. 1997), whereas a 2 $M_{\rm Jup}$ brown dwarf at an age of 1 Gyr in the solar neighborhood could be detected only within $\sim$ 3 pc ($<$ 0.5 pc for 5 Gyr, Burrows et al. 2003) with the most sensitive wide-field survey for cold brown dwarfs (WISE, Wright et al. 2010).

The Taurus star-forming region is one of the most promising sites for measuring the mass function below the current limits of $\sim$10 $M_{\rm Jup}$. It is among the nearest major groups of newly formed stars (140 pc, Wichmann et al. 1998) with a statistically significant population ($\sim$450 members). We have measured the IMF for Taurus down to $\sim$20 $M_{\rm Jup}$ for an extinction and spatially limited sample (Luhman 2004; Luhman et al. 2009; Luhman et al. 2017). We have also completed the census for all disk-bearing members for objects $\gtrsim$30 $M_{\rm Jup}$ using *WISE* photometry (Esplin et al. 2014).

We are seeking to expand the census of Taurus to the point that it is nearly complete down to 5 $M_{\rm Jup}$ for an area that encompasses most of the known members, which will improve the constraints on the substellar mass function and its minimum mass. Using optical and IR photometry from Gaia DR1 (G), PanSTARRS-1 ($grizy$), SDSS ($ugriz$), 2MASS (JHK_s), UKIDSS ($zYJHK_s$), WISE (3.5, 4.5 μm), and IRAC on *Spitzer* (3.6, 4.5, 5.8, 8.0 μm), we have identified candidate brown dwarfs with positions in color-magnitude diagrams similar to the known members. Among these datasets, UKIDSS and IRAC reach the lowest masses. Three examples of our color-magnitude diagrams are shown in Figure 1. We further refined the candidates from those diagrams using proper motions derived from astrometric measurements from the various surveys that provided the photometry. To determine if they are members and to measure their spectral types, we have obtained near-IR spectra of 26 candidates with Gemini and IRTF, 15 of which were confirmed as new members of Taurus (Esplin et al. in prep). They have masses extending down to 5 $M_{\rm Jup}$ according to evolutionary models (Burrows et al. 1997; Chabrier et al. 2000; Baraffe et al. 2015). We propose to obtain spectroscopy of the remaining 39 candidates with the Red Channel Spectrograph and MMIRS.

To reliably identify candidate brown dwarfs, we need photometry in at least three bands from among $zYJHK_s$. The deepest available data of this kind in Taurus consist of YJK_s from UKIDSS, which cover a large portion of the region (see Figure 2) and have been used in our candidate selection to date. The limiting magnitude of that selection is set by the Y data (i.e., Y is less sensitive to brown dwarfs than J and K_s). To extend our search for brown dwarfs to fainter magnitudes (lower masses), we propose to obtain images of an area encompassing a majority of the Taurus population in the H band with WFCAM, which offers similar sensitivity to brown dwarfs as J and K_s but was not included in the UKIDSS observations of the region. We will also obtain J and Y images of the major stellar aggregates that lack data in those bands.

References

Baraffe, I., Hormeier, D., Allard, F., & Chabrier, G. 2015, A&A, 577, 42
Bate, M.R., Bonnell, I.A., & Bromm, V. 2002, MNRAS, 332, L65
Bonnell, I. A., Clark, P., & Bate, M. R. 2008, MNRAS, 389, 1556
Burrows, A., Sudarsky, D., & Lunine, J. I. 2003, ApJ, 596, 587
Burrows, A., et al. 1997, ApJ , 491, 856
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Esplin, T. L., Luhman, K. L., & Mamajek, E. E. 2014, ApJ, 784, 126
Hennebelle, P, & Chabrier, G. 2008, ApJ, 684, 395
Hester, J. J., et al. 1996, AJ, 111, 2349
Kirkpatrick, J. D., et al. 2012, ApJ , 753, 156
Larson, R. B. 1992, MNRAS, 256, 641
Low, C., & Lynden-Bell, D. 1976, MNRAS, 176, 367
Lucas, P. W., et al. 2001, MNRAS, 326, 695
Luhman, K. L. 1999, ApJ , 525, 466
Luhman, K. L. 2004, ApJ, 617, 1216
Luhman, K. L. 2012, ARAA, 50, 65
Luhman, K. L., Liebert J., & Rieke, G. H. 1997, ApJ, 489, L165
Luhman, K. L., et al. 2009, ApJ , 703, 399
Luhman, K. L., et al. 2017, AJ, 153, 46
Martìn, E. L., Rebolo, R., & Zapatero Osorio, M. R. 1996, ApJ, 469, 706
Padoan, P. & Nordlund, Å. 2002, ApJ, 576, 870
Reipurth, B., & Clarke, C. 2001, AJ, 122, 432
Whitworth, A.P., & Zinnecker, H. 2004, A&A, 427, 299
Whitworth A, et al. 2007, Protostars and Planets V, 459
Wichmann, R., Bastian, U., Krautter, J., et al. 1998, MNRAS, 301, L39
Wright, E. L., et al. 2010, AJ, 140, 1868

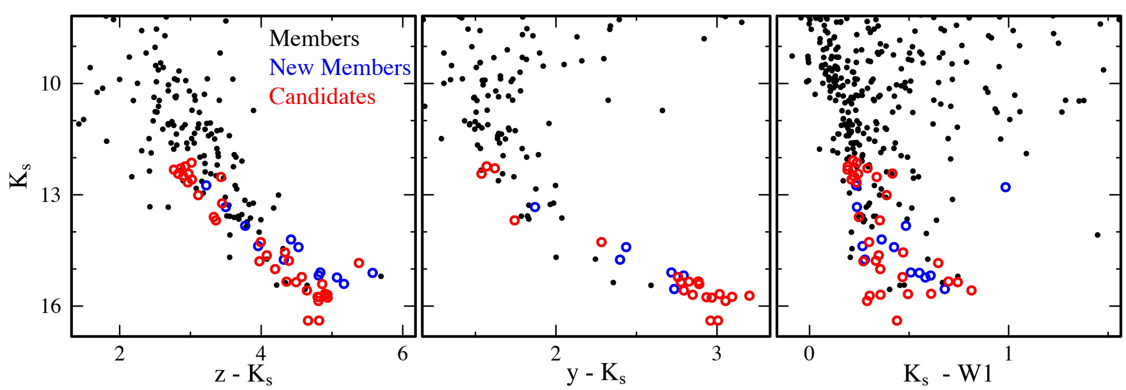

Figure 1: Color-magnitude diagrams for the known members of Taurus (black points) and candidate low-mass members (open circles) that we have identified with these diagrams and others. Some of these candidates should be among the least massive known brown dwarfs in Taurus if they are members ($\sim$5 M_{Jup}). We obtained spectra of 26 candidates with Gemini and IRTF, 58% of which were confirmed as members (blue). We propose to observe the remaining 39 candidates with the Red Channel Spectrograph and MMIRS (red).

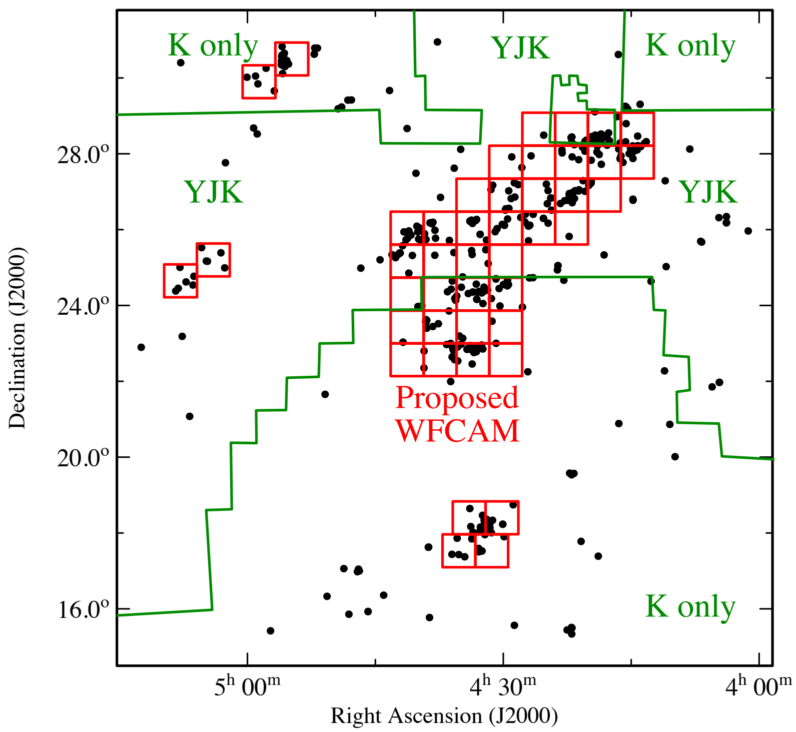

Figure 2: Spatial distribution of the known members of Taurus (black points). UKIDSS observations of Taurus have produced some of our best candidate brown dwarfs (see Fig. 1), but they do not encompass all of the major aggregates in at least three bands (green lines). We propose to observe the majority of Taurus in H, which was not included by UKIDSS, and portions in Y and J that lack such data (red lines). We will use these data to identify candidate brown dwarfs across a larger area and at lower masses.

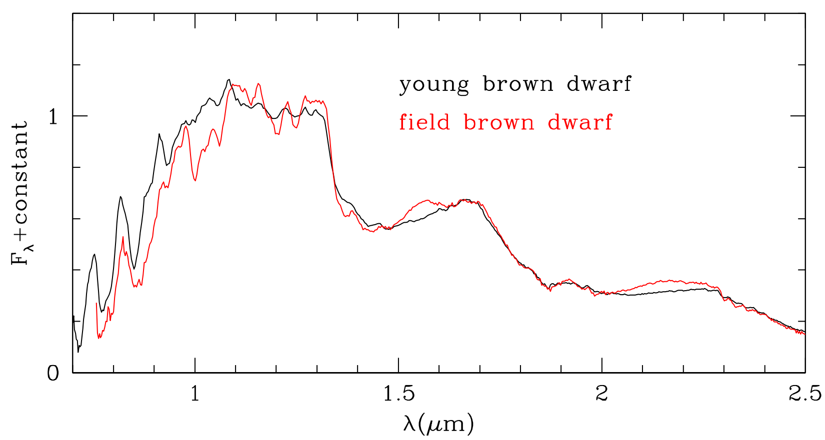

Figure 3: Comparison of the low-resolution near-IR spectra of a young brown dwarf and an older field dwarf. A young brown dwarf can be distinguished from an old dwarf based on gravity-sensitive features, such as FeH at 0.99 μm and the shape of the continuum near 1.6 μm. We propose to use data of this kind to measure spectral types and confirm the youth and membership of the brown dwarf candidates in Taurus.

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)***

Optical and near-IR spectroscopy

For our 39 candidate members of Taurus that lack spectroscopy, we propose to obtain spectra with the Red Channel Spectrograph and MMIRS to measure their spectral types and confirm their membership. We will distinguish between young objects and field dwarfs with gravity-sensitive features such as Na I, K I, FeH, and the shape of the H-band continuum (See Figure 3, Martìn et al. 1996; Luhman et al. 1997; Lucas et al. 2001). We will measure spectral types from these data through comparison to members of other members of star-forming regions that we have previously classified (Luhman 1999; Luhman et al. 2017).

We will obtain optical spectra of the 17 candidates with $i < 20$ with the Red Channel Spectrograph. The spectrograph will be operated with the 270/7300 grating, the R-63 filter, and the 0.75$''$ slit, which provides coverage from 6000–9000 Å and a resolution of 11.4 Å. To estimate the time needed for this program, we rely on our previous experience with similar spectrographs: COSMOS on the CTIO 4 m and GMOS at Gemini Observatory. These spectrographs achieve a typical sensitivity of SNR = 30 in a 1800 sec exposure for a i = 16 (COSMOS) and 18 (GMOS) with configurations similar to the one we propose to use on the Red Channel. Because the diameter of the MMT is intermediate between CTIO and Gemini, we expect to achieve a similar SNR for i = 17. Given the range of magnitude of our targets (16 – 20) and an overhead of $\sim$10 min per target, we estimate that we can obtain spectra for $\sim$1.5 targets per hour with SNR=30, which is the minimum necessary for our spectral classifications. To observe our 17 targets, we request 11 h or $\sim$1 night. Because our targets are at $>$2 airmass for only 9 hr per night, we would prefer two half nights (second half) in Oct – Nov.

We will obtain near-IR spectra of the 22 candidates with $i < 20$ MMIRS. The spectrograph will be operated with the HK grism, HK3 filter, and the 0.8$''$ long slit, providing coverage from 1.2–2.3 μm and R=700. According to the MMIRS exposure time calculator, we can achieve a SNR=12 in 100, 600, and 1800 sec for $H = 15.5$, 16.5, and 17.5 objects, respectively (the typical magnitudes of these candidates). This SNR can be increased by smoothing the spectra to lower resolution, which will be sufficient for accurate classification. Given the time for setup (10 min per target), readouts and dithers (10 sec per exposure), and telluric standard observations (10 min per 2 h of observations), we require 11 hr to complete our observations or $\sim$1 night.

Near-IR imaging

To extend our survey to a larger area and lower masses, we will obtain YJH imaging for areas that lack such data in UKIDSS. By combining the photometry and astrometry from the proposed imaging with previous data, we will identify candidate brown dwarfs based on both color-magnitude diagrams and proper motions. In future semesters, we will propose to obtain spectroscopy of the candidates identified in these data to confirm their membership in Taurus.

To reach the sensitivity of UKIDSS in our proposed images, we will employ the same observing strategy in that survey. Each Y tile will consist of four observations of two 20 sec exposures at two offset positions, which will take 268 sec (including overheads). Each of the J and H tiles will consist of four observations with 10 sec exposures at 4 offset positions, which will take 294 sec per tile. We will observe 19, 19, and 44 tiles in Y, J, and H, respectively, which we indicate in Figure 2. Assuming we take photometric standard observations four times a night, we need 7 h to complete this observing run or $\sim$1 night.

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**)*

(1) We have not used any UAO nights on this project. We are currently requesting three nights to complete the photometric survey of Taurus and to obtain spectroscopy of 18 candidate brown dwarfs. We anticipate the need of one to two nights in a future for spectroscopic classification of additional candidate brown dwarfs we will identify.

(2) The spectroscopic targets of this program were selected from photometric and astrometric data obtained from Gaia, 2MASS, Pan-STARRS1, and UKIDSS. The proposed observations will confirm the cool nature and youthful nature of candidate brown dwarfs identified in those data and will provide photometric data for the regions of Taurus not fully imaged by UKIDSS.

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**)*

None

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*

The PI is at the beginning of postdoc appointment and this request is the start of a program to search for the bottom of the initial mass function in several nearby star-forming regions.

Object	RA	DEC	i	J	H	K	instr
Taurus	04:30:00.00	25:00:00.0	NA	NA	NA	NA	WFCAM
T2919196	04:28:58.59	15:17:38.6	15.84	13.06	12.38	12.08	RED
T2897168	04:45:12.73	30:28:03.9	16.05	13.21	12.61	12.32	RED
T2859497	04:55:21.70	27:05:22.0	16.06	13.29	12.61	12.29	RED
T185708	04:00:27.89	20:31:59.0	16.14	13.15	12.56	12.23	RED
T1243911	04:48:21.76	29:28:05.0	16.30	13.04	12.52	12.13	RED
T1315845	04:33:56.22	30:20:44.7	16.30	13.42	12.73	12.45	RED
T2917679	04:38:17.54	15:58:36.0	16.33	13.43	12.84	12.50	RED
T2070755	05:00:43.35	18:47:13.3	16.64	13.54	13.03	12.67	RED
T2868330	04:59:30.88	28:47:23.2	16.68	13.54	12.93	12.59	RED
T160879	04:20:49.33	21:15:07.3	17.03	13.76	12.96	12.54	RED
T2964937	05:00:02.85	18:28:48.5	17.14	13.98	13.38	13.01	RED
T1287669	04:34:35.48	28:57:26.1	17.71	13.93	13.26	12.95	RED
T2811977	04:23:32.91	19:50:19.3	17.96	13.78	13.03	12.59	RED
T2888414	05:09:59.08	30:36:45.4	17.98	14.27	13.70	13.23	RED
T2922086	04:23:24.22	15:59:53.8	18.16	14.65	13.99	13.60	RED
T2815965	04:00:54.83	21:17:21.1	18.32	14.72	14.13	13.69	RED
T600617	04:28:59.66	24:25:49.4	19.91	16.33	15.24	14.63	RED
T2850432	04:26:30.58	27:03:56.6	20.15	16.15	15.35	14.81	MMIRS
T2962068	04:44:38.39	17:00:01.5	20.15	16.45	15.20	14.55	MMIRS
T2850537	04:29:05.11	27:05:56.3	20.23	16.00	15.12	14.42	MMIRS
T2851049	04:25:24.86	27:26:52.7	20.40	16.50	15.26	14.78	MMIRS
T2986996	04:46:46.75	21:37:39.5	20.71	16.23	15.54	15.00	MMIRS
T2904736	04:11:37.56	28:28:55.0	21.01	17.03	15.81	15.34	MMIRS
T2858213	04:59:09.55	26:45:43.4	21.02	16.87	15.81	15.22	MMIRS
T2904737	04:11:31.02	28:29:33.8	21.12	17.01	15.79	15.36	MMIRS
T4962119	04:41:51.20	25:27:36.3	21.72	17.58	16.69	15.76	MMIRS
T4112615	04:56:36.84	30:28:23.3	21.88	17.13	16.43	15.67	MMIRS
T4923088	04:41:10.54	25:18:41.7	21.89	17.68	16.76	15.79	MMIRS
T4839699	04:41:25.81	24:59:03.9	21.91	17.67	16.76	15.80	MMIRS
T3395199	04:11:06.69	28:16:52.3	21.91	17.70	16.80	15.86	MMIRS
T2850879	04:26:23.19	27:16:38.8	21.99	17.05	15.88	15.41	MMIRS
T2981609	04:36:42.68	19:01:35.2	22.01	17.12	15.66	14.84	MMIRS
T4681536	05:04:18.06	24:23:02.3	22.43	17.26	16.50	15.70	MMIRS
T3669978	04:58:35.14	29:09:35.8	23.27	17.78	16.78	15.74	MMIRS
T7462337	04:24:48.09	27:36:33.9	23.44	18.02	17.23	16.39	MMIRS
T7409841	04:39:06.48	25:29:27.5	23.50	18.28	17.36	16.39	MMIRS
T7798499	04:23:18.57	25:01:33.4	24.17	18.10	17.03	15.92	MMIRS
T7425897	04:41:08.33	25:22:29.6	24.76	18.28	17.17	16.01	MMIRS
T7500957	04:39:07.76	26:42:36.0	24.93	18.20	17.02	15.78	MMIRS

Gmail

Taran Esplin <greenlife42@gmail.com>

Observing with MMIRS

McLeod, Brian <bmcleod@cfa.harvard.edu>
To: Taran Esplin <taran.esplin@gmail.com>

Mon, Mar 6, 2017 at 4:31 PM

Hi Taran,

Hopefully all the info you need can be found here:
https://www.cfa.harvard.edu/mmti/mmirs.html
Instrument description for observers, and manual.

Feel free to submit your proposal, but don't hesitate to ask if you have any questions.

Brian

[Quoted text hidden]