OBSERVING REQUEST
University of Arizona Observatories

Year: 2021 **Term:** Feb–Jul **Proposal type:** short-term

Dynamical Survey for Brown Dwarfs and Giant Planets in Scorpius-Centaurus

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CoI(s):

Abstract of Scientific Justification

The physics of broad dwarfs and giant planets are difficult to model, and rely on assumptions like clouds and metalicity to relate observable quantities like luminosity to physical properties like mass and radius. Mass measurements independent of evolutionary and atmospheric models are necessary to test brown dwarf and giant planet physics, which requires dynamical observations of low mass companions to main sequence stars. However, these companions have been found to be quite rare. Surveys to identify new low-mass companions need to be optimized to increase the likelihood of discovery. The Hipparcos-Gaia Catalog of Accelerating Stars (HGCA) identified stars with significant accelerations over the 24 year baseline between the two missions, indicating a likely hidden companion. We propose a survey of stars identified in HGCA in the young Scorpius-Centaurus OB moving group to discover new low-mass companions in this well-characterized association. We developed a target list of 47 stars optimized for companion discovery via HGCA. We propose to use the MagAO-CLIO and VisAO cameras on Magellan Clay telescope to accomplish our survey.

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	MAG1		MagAO			8	any	Mar–Aug	Jan–Oct	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*:

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	List attached			

Approval for Instrument Use from PI: ____________________

(have instrument PI send confirmation email to TAC chair

Graduate students *(If graduate students are listed as investigators, the advisor must email the TAC Chair to confirm general approval and also describe the specific role of the proposed research in each student's 2nd-year project and/or thesis.)*

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

Scientific Justification

Brown dwarfs (BD) are enigmatic[1]. In the absence of a sustained nuclear energy source [2], BD properties do not follow clear power law relations in the same way as main sequence stars. While models born from the well-known ideal gas equation of state, composition, convection, cloud formation, and opacity all complicate the physics of the BD and make observable quantities like luminosity and effective temperature (T_{eff}) difficult to predict (Burrows & Liebert 1993, Burrows et al. 2001). BDs lack a universal mass-radius relation; objects of mass ∼1-70 M_{Jup} are all near ∼1 R_{Jup}, and T_{eff} is independent of mass (Burrows & Liebert 1993). Evolutionary BD models are highly dependent on assumptions about metallicity, helium fraction, and presence of clouds, and yield very different estimates of properties like age based on what is assumed in the model (Burrows et al. 2011). Importantly, an object's initial energy and entropy at formation ("hot-start" vs "cold-start" models) determines its evolutionary pathway, and is a key factor in predicting luminosity and age, yet must be assumed in evolutionary models (Bowler 2016). Similarly, BD atmospheric models are highly sensitive to assumptions. Numerous isochrone models with varying assumptions exist (e.g. BHAC2015 evolutionary models (Baraffe et al. 2015), BT-Settl atmosphere models (Allard et al. 2012)), which yield differing results for estimates of mass, radius, age, and surface gravity from observed quantities like luminosity and T_{eff}. However, an accurate measurement of the mass of an individual object, and the mass distribution of the BD population, is key for understanding the physics of these objects and how they fit into the star and planet formation picture.

The only way to obtain a model-independent BD mass is dynamically, which requires observation of a BD companion to a main sequence star, preferably one with well-known mass and age, over time. By observing the orbital motion of the two-body system, with the well-known mass of the host star (or by including the host star mass in the fit), we can derive the mass of the BD companion purely through kinematics, with no model assumptions needed. Indeed, independent masses are a direct observational test of model assumptions like hot-start vs cold-start models.

However, while isolated BDs are common (Burrows et al. 2011), BD companions are quite rare. Numerous BD and giant planet companion searches have been carried out, all with occurrence rates in the low single-digits (Bowler 2016). Surveys targeting young star forming regions, where these objects will be brightest in infrared wavelengths, fail to turn up more than a handful of BD or giant planet companions. Clearly a method for developing smarter target lists is needed find these companions, if they are out there.

The precision of *Gaia* astrometry promises to uncover previously unresolved companions by observing the reflex acceleration of the host star due to the companion's mass, and will find numerous planets astrometrically. However, due to the observation time-frame of a few years, many of the discovered companions will not be reachable by direct imaging, where their photometry and spectra could be observed directly. For that, companions on wider orbits with longer orbital periods are desired.

Enter the Hipparcos-Gaia Catalog of Accelerations (HGCA; Brandt 2018). HGCA combines *Gaia* with astrometry from the *Hipparcos* mission into a common reference frame, and objects present in both catalogs have independent velocity measurements spanning a 24 year baseline. Stars which have accelerated in the plane of the sky during that time frame point to a previously hidden companion which may be reachable by direct imaging data processing techniques. Figure 1 displays how the presence of a companion can create a difference in the velocity vectors from one epoch to the next. By giving clues to the presence of an unseen companion, the HGCA catalog allows us to develop smart target lists to increase likelihood of detection of companions, finding more systems to conduct population studies of BDs and giant planets.

HGCA acceleration terms are already being exploited to give better dynamical mass constraints than astrometric time-series alone, and to test BD and giant planet formation and evolutionary theories. Bowler et. al.

[1] It is common practice to distinguish low mass brown dwarfs from high mass giant planets at a cutoff of M≈13 M_{Jup}. For the purposes of this discussion we treat giant planets as extensions of the brown dwarf mass distribution, and include giant planets in the following disucssion

[2] BDs (>∼13 M_{Jup}) burn deuterium early in their lifetimes, and solar-metallicity BDs with masses above ∼ 63M_{Jup} can burn lithium, however neither nuclear source is sufficient to balance radiative losses and prevent the object cooling with age. (Burrows et al. 2001)

(2018) used radial velocity and relative astrometric measurements to determine the dynamical mass of the companion to GJ 758, and used this independent mass measurement to test several brown dwarf evolutionary models. Calissendorff & Brown (2018) then improved on the mass measurement by exploiting multi-epoch astrometry from HGCA. Dupuy et al. (2019), following Snellen & Brown (2018), refined the mass and eccentricity of the giant planet β Pic b using HGCA, and found it is inconsistent with cold-start models but consistent with hot-start models, the first model-independent test of these theories. No new companions have yet been discovered using the HGCA.

Meaningful study of BD physics by comparing observable quantities like luminosity and effective temperature to predictions can only be accomplished with a larger sample of BD populations with model-independent masses than currently exists. Given the dearth of BD and giant planet companions discovered in surveys of young star forming regions to date, a survey target list should be developed that has a higher likelihood of actually discovering new companions.

We propose a search for BD and giant planet companions to young stars in the Scorpius-Centarus OB Association (ScoCen) using a smart target list developed from the HGCA using MagAO/VisAO on Magellan Clay telescope. ScoCen is ideal because component membership has been well studied (Rizzuto et al. 2011, Wright & Mamajek et al. 2018), and has a young age ($\tau \approx$10 Myr; Rizzuto et al. 2016, Pecaut & Mamajek 2016), where these objects will be bright in IR wavelengths. It is one of the nearest star forming regions ($d \approx 145$pc), so the diffraction limit of MagAO reaches a closer separation than for more distant regions (e.g. for K' band, λ = 2.2μm, λ/D = 70 mas = 10 AU at $d = 145$pc). It is also entirely reachable by southern hemisphere telescopes.

We will utilize MagAO/VisAO due to MagAO's ability to achieve nearly diffraction-limited point spread functions, the wide range of filter bands available in IR with MagAO, and the ability to simultaneously image the same target in visible wavelengths with VisAO (Figure 2). Photometry in multiple IR and visible bands is essential to establish colors and estimate spectral type and effective temperature of discovered companions (an example of our group performing this analysis is shown in Figure 3, and can be found in Males et al. 2014). We will observe in ADI mode to accomplish PSF subtraction to uncover possible closer companions.

References:

Allard, F., Homeier, D., & Freaytag, B., 2012, RSPTA, 370, 2765;
Baraffe, I., Homeier, D.,Allard, F., & Chabrier, G., 2015, AAP, 577, A42;
Bowler, B. P., 2016, PASP, 128, 102001;
Bowler, B. P., Dupuy, T. J., Endl, M., et al. 2018, AJ, 155, 159;
Brandt, T. D., 2018, ApJS, 239, 31;
Burrows, A., Hubbard, W. B., Lunine, J., I., & Liebert, J., 2001 RvMP, 73, 719;
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Rizzuto, A. C., Ireland, M. J., Dupuy, T. J., & Kraus, A. L. 2016, ApJ, 817, 164;
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Snellen, I. A. G. & Brown, A. G. A., 2018, NatAs, 2, 883-886;
Wright, N. J., & Mamajek, E. E., 2018, MNRAS, 476, 381

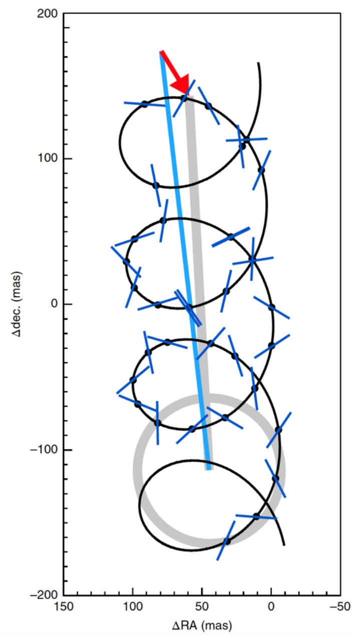

Figure 1: Snellen & Brown (2018) Figure 1. An illustration of the astrometric acceleration of Beta Pic due its companion. Black line shows parallactic motion, blue points are Hipparcos measurements. The grey shows the separation of parallax motion (circle) from proper motion (line) in *Hipparcos*, and light blue shows the proper motion measured by *Gaia*. Red arrow indicates the direction and (exaggerated) magnitude of the acceleration vector due to the influence of the companion.

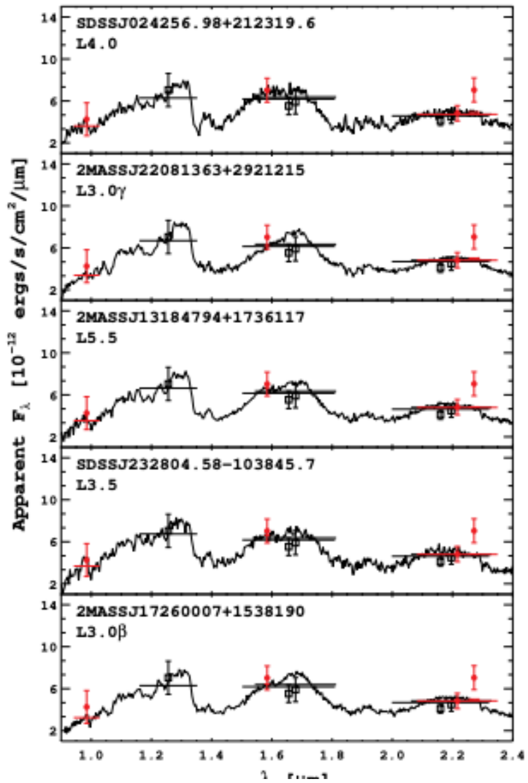

Figure 3: Males et al. (2014) Figure 11. An example of using photometry in multiple filter bands to fit library spectra and constrain spectral type for the giant planet β Pic b. The red points are photometric fluxes obtained by MagAO-CLIO of VisAO cameras, the black are literature values. The black lines are SDSS library spectra for template objects representative of BD spectral types.

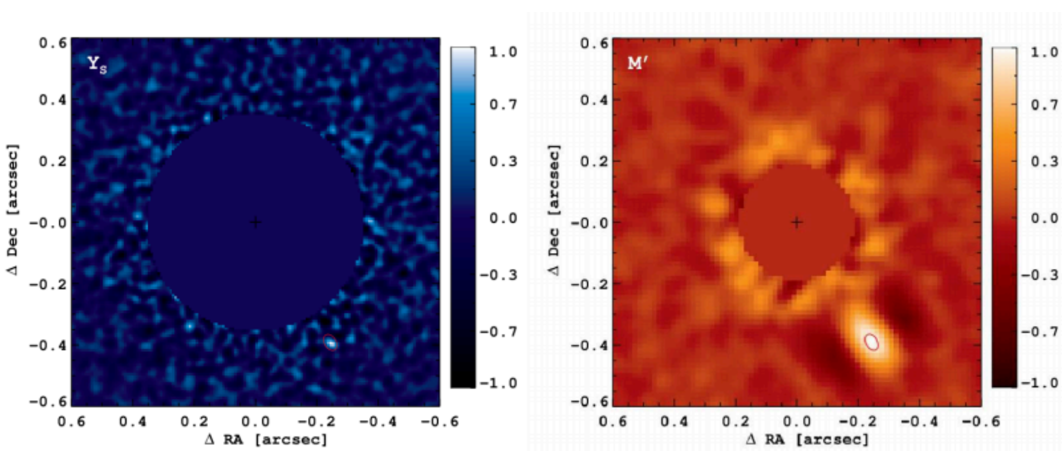

Figure 2: Males et al. (2014) Figure 2. Simultaneous detection of β Pic b with VisAO (left) and MagAO-CLIO (right). Red ellipse denotes MagAO position uncertainty; central starlight had been removed in post-processing.

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)***

Target selection: We cross-matched the Hipparcos-Gaia Catalog of Accelerating Stars (HGCA) against the ScoCen membership list of Rizzuto et al. (2011), which returned 102 candidate ScoCen members in the HGCA. We sorted the cross-matched list by HGCA χ^2 value, which parameterizes the significance of the acceleration measurement, and retrieved the *Gaia* Re-normalized Unit Weight Error (RUWE) value, which parameterizes the goodness of fit of *Gaia*'s single star model. We excluded known double stars, and stars with large RUWE, which likely indicates a large companion that will be resolved by *Gaia* future data releases. We searched for objects with RUWE ≈ 1.0, and relatively high HGCA χ^2 as the best candidates for hidden companions that won't be uncovered by *Gaia* (as recommended in Brandt 2018). We excluded stars who have objects in *Gaia* within 30″with similar parallax, indicating a likely wide binary, and excluded stars with parallax $\pi < 5$ mas and $\pi > 10$ mas to select objects near the mean distance for ScoCen. This gave 47 objects comprising our target list. The attached target list is ordered by ScoCen membership probability reported in Rizzuto et al. (2011), which is our observing priority.

Full target list attached

Observing strategy: Each target should be observed in multiple filter bands with MagAO-CLIO camera and simultaneously with VisAO.

MagAO-CLIO: We will first observe each target with K′ filter, since young objects should be bright in these wavelengths. Then observe in filters L′, 3.9 μm, M′, $J_{\rm MKO}$, and $H_{\rm MKO}$ (in order of priority). For each filter, we will observe in ABBA nod mode with 5 images each nod, with 3 seconds of integration time per coadd for $\sim$10 coadds per image, without combining coadds. We will adjust integration time as necessary if stars become saturated. All stars in the target list are similar magnitudes in Gaia G band, so the same settings should apply relatively equally to all targets. We will observe with the rotator off to utilize ADI post processing.

VisAO: VisAO observations should be carried out simultaneously to MagAO-CLIO. Filter priority is r′, z′, Hα, and y. Exposure time should be as needed to maximize flux without saturating the psf. IR observations should drive the observing strategy; obtain some Vis images in different filters as allowed during IR observations

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**)*

MagAO-CLIO observations comprise 1 hour per target, with 47 targets, gives 50 hours to complete the observing program. We request 8 nights sometime in period from January to August for optimal positions for the entire target list. We have had no previous UAO nights for this project, and no non-UAO time.

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**)*

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**)*

Full Target List					
HipID	GaiaRA	GaiaDEC	MemProb	HGCA χ^2	GaiaGMag
72627	222.744493	-42.822618	93	245.0	6.796734
71321	218.772141	-43.554645	92	282.0	7.784425
78196	239.497198	-31.729040	90	66.0	7.008297
68532	210.440239	-39.438720	89	605.0	7.512680
76633	234.750173	-19.732635	89	16.0	7.613636
66454	204.347646	-46.427969	89	30.0	5.879077
67957	208.755192	-50.750674	89	1021.0	9.066534
61087	187.802322	-61.908794	88	800.0	7.861641
60459	185.925438	-63.870124	88	168.0	7.375116
73913	226.574628	-35.406293	88	351.0	8.627187
58416	179.661975	-52.768752	87	92.0	7.440931
67199	206.560177	-54.683476	86	516.0	6.407881
79392	243.041159	-23.921628	86	581.0	8.384354
61049	187.692493	-58.188055	85	15.0	8.428329
60851	187.079882	-64.341037	82	21.0	6.027140
59603	183.342818	-56.893278	82	122.0	8.437284
64053	196.909245	-53.459855	82	13.0	5.677557
69302	212.770175	-49.273235	82	365.0	8.465155
57710	177.529765	-49.543234	81	226.0	8.169823
56963	175.160539	-49.509227	81	1397.0	7.808117
62428	191.913062	-58.297635	81	489.0	6.884530
65822	202.400499	-47.875899	81	374.0	6.906934
77815	238.341305	-21.971398	79	64.0	8.317451
58884	181.161584	-68.328947	78	17.0	5.943500
65219	200.487837	-51.282327	78	76.0	7.048570
62171	191.110541	-54.346766	78	136.0	8.785447
77388	236.963058	-38.260144	78	188.0	8.009127
74479	228.281809	-36.091527	78	27.0	6.064933
58146	178.869908	-62.196452	77	42.0	7.752351
62026	190.707080	-55.947042	77	1648.0	6.030624
66651	204.940340	-54.148212	75	104.0	7.321187
77295	236.715089	-36.936947	74	12.0	7.932561
64322	197.745699	-62.087787	74	1045.0	8.126640
62032	190.728421	-50.816729	73	21.0	8.661253
78754	241.176287	-37.816228	73	872.0	7.035934
78918	241.648003	-36.802409	72	12.0	4.105694
60855	187.093458	-39.041219	70	70.0	5.419561
70809	217.216112	-47.992173	68	50.0	6.361968
62683	192.671360	-33.999407	62	211.0	4.806796
59119	181.844948	-32.661900	60	40.0	7.624681
72158	221.385177	-26.942764	59	73.0	7.996533
81447	249.522988	-34.019729	59	185.0	8.913421
81914	250.975267	-41.113438	58	161.0	6.104403
80711	247.185673	-17.477755	53	123.0	8.902443
75613	231.739125	-44.107654	52	56.0	7.681859
70483	216.254076	-37.447179	52	130.0	6.640736
58901	181.188259	-59.253305	51	349.0	6.274603