OBSERVING REQUEST
University of Arizona Observatories

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

Nature or Nurture: measuring differences in the jets from dust pillars and small globules in the Carina nebula

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Abstract of Scientific Justification

We propose to use the FIRE spectrograph on Magellan I to obtain near-IR spectroscopy of seven protostellar jets in the Carina nebula to study powerful jets and entrained outflows emerging from small, compressed globules. Recent multiwavelength imaging and spectroscopy reveal that different emission lines trace different outflow components. Bright, near-IR [Fe II] emission traces neutral material in self-shielded protostellar jets. For some deeply embedded sources, the [Fe II] jet emerges out of a sheath of entrained molecules traced by slower H_2 emission that survives only briefly in the H II region. Several jets show Hubble-like velocities in Hα spectra, similar to the Hubble wedges observed in some molecular outflows, but unlike the steady jet-like velocities traced by [Fe II] emission. Together, these data suggest that the HH jets in Carina are, in fact, externally irradiated outflow systems with [Fe II] emission tracing the jet, H_2 emission from molecules entrained by the jet, and Hα emission from the ionized skin of the externally irradiated outflow sheath. To test this hypothesis, we request seven targets that sample a range of environments from compressed globules to protostars that are unobscured in the H II region in order to test whether environment is the key discriminant that determines whether a jet entrains an appreciable molecular outflow. With the slit aligned along the jet axis and wavelength coverage over $0.8 - 2.5$ μm, we will detect [Fe II] and H_2 simultaneously, and compare their spatial distributions. In addition, new spectra will support an accepted *HST* WFC3-IR program to image [Fe II] emission from a larger sample of jets in Carina, allowing us to constrain the jet velocities and the physics of jets driven by a sample of intermediate-mass protostars.

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	f/11	FIRE			3	bright	Feb–Mar	Jan–Apr	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Please avoid Jan 3-9 (MR at AAS).

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	HH 903	10:45:56.6	−60:06:08.0	$K = 10.8$
2	HH 1006	10:46:33.0	−60:03:54.0	$K \approx 15$
3	HH 1010	10:45:48.7	−59:43:38	$K = 14.3$
4	HH 1011	10:45:04.9	−59:26:59	$K = 10.8$
5	HH 1013	10:44:19.2	−59:26:14	$K = 13.4$
6	HH 1014	10:45:45.9	−59:41:06	$K \approx 15$
7	HH 1018	10:44:52.9	−59:45:26	$K = 13.4$

Approval for Instrument Use from PI: ______________________________

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

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
Megan Reiter	Nathan Smith		no	yes

Scientific Justification

New optical and IR images and spectroscopy reveal discrepancies in the morphologies and Doppler velocities traced by different emission lines for several HH jets in Carina. Two trends have emerged from the small sample of well-studied sources. (1) When Hα and [Fe II] trace different morphologies in images, they also tend to have different kinematics in spectra. (2) Jets driven by deeply embedded protostars have extended H_2 emission along the jet axis outside the natal pillar. Bright near-IR [Fe II] emission is common to all jets observed in Carina, however, not all jets show a discrepancy in the Hα and [Fe II] velocities and not all jets have near-IR H_2 emission. We propose to obtain near-IR spectroscopy of seven jets in the Carina nebula with FIRE on Magellan to determine the role that environment plays in shaping the Hα and H_2 emission from the jet. These spectra fill a gap in the range of environments sampled in P.I. M. Reiter's survey to measure the physical properties of jets driven by intermediate-mass protostars.

Unlike outflows in more quiescent regions, the jets targeted in this proposal emerge into a giant H II region created by more than 65 O-type stars in the Carina nebula where the harsh UV radiation field irradiates the jet, illuminating even unshocked material. Hα emission traces the ionized jet skin where Lyman continuum radiation photoevaporates the jet. For sufficiently dense jets (like those in Carina), most of the jet mass is in neutral gas behind the ionization front (see Figure 2), traced by near-IR lines of [Fe II] that are collisionally de-excited in the otherwise invisible dense jet core [4]. New, near-IR [Fe II] images from *HST* reveal collimated jets that in some cases, diverge significantly from the morphology traced by the Hα emission. Both HH 666 and HH 900 have broad Hα emission near the driving source that envelopes a bright, collimated [Fe II] jet [4, 7]. Recent near-IR spectroscopy with FIRE indicate that the discrepancy between optical and IR tracers extends to the velocity structure as well (see Figure 1). Strong [Fe II] emission traces a steady velocity from either side of the jet, in contrast to the Hubble-like flow apparent in Hα spectrum (see Figure 1 and [8, 6, 7]). Increasing velocity with increasing distance from the source, as in the Hα spectrum, suggests a short-duration eruption that accelerated material toward the culminating shocks. In this picture, the sudden increase in the jet mass-loss rate provides the "kick" that accelerates the ambient material, creating the Hubble-like flow in the Hα velocity structure. The initial "kick" may also clear a path for the jet, explaining why the [Fe II] emission does *not* show a decrease in velocity (resulting from shock interaction with the environment). Hubble wedges have been observed in the position-velocity diagrams of molecular *outflows*, although they have only been seen in a few *jets* (e.g. [8, 7]).

Despite these observed similarities, HH 666 and HH 900 sample distinctly different evolutionary stages and environments. The HH 666 driving source can be identified at optical wavelengths, and the dynamical age of the jet places it among the most evolved sources in Carina [5]. HH 666 appears to originate at the center of a $\sim 40''$ wide translucent dust pillar that shields the jet from Lyman continuum radiation, but permits irradiation of the jet by the Balmer continuum, illuminating the inner jet. In contrast, the dynamical age of HH 900 is an order of magnitude shorter than HH 666 and bright [Fe II] emission from the jet begins $\sim 1\farcs5$ way from the edge of the globule. The outflow axis defined by the [Fe II] jet points to a young protostar completely obscured within the small ($\sim 1\farcs5$) natal globule [7]. Discrepancies in the Hα and [Fe II] morphologies and kinematics common to these two otherwise disparate sources suggests external irradiation from the environment is key, illuminating separate jet components. If this is correct, [Fe II] emission will trace jet-like velocities regardless of the evolutionary stage of the driving source. To test this hypothesis, we will measure the jet velocity traced by [Fe II] emission as a function of position in seven jets emerging from environments ranging from small, dense globules, to unobscured protostars.

In [7], we propose that the jets in Carina entrain an outflow like their counterparts in more quiescent regions, but that the outflow is observed in Hα emission because external irradiation in the H II region ionizes the skin of the outflow. Unlike molecular outflows in quiescent regions, the jets in Carina emerge from the protection of their natal globule into an H II region where molecules will be blasted by the harsh UV radiation of the many nearby O-type stars and rapidly destroyed. Thus, extended H_2 emission from the outflow is not expected. However, AO images of HH 900 reveal H_2 emission outside the globule that follows the broad outflow morphology of the Hα emission. FIRE spectra of HH 900 demonstrate that H_2 emission traces lower velocities than [Fe II], and that the location of the two emission lines in the jet are mutually exclusive (see Figure 2). Ground-based H_2 images hint at possible extended H_2 emission from other jets that emerge from dense globules [1]. A large column of entrained molecules that shield the inner jet may also explain why [Fe II] emission from the jet appears to be offset from the globule edge (as in HH 900, see Figure 2 and [4]). FIRE spectra of HH 1066, another jet emerging from a small globule in Carina, reveal H_2 emission very near the IR-bright (but optically invisible) driving source that is clearly extended, but does not trace the full length of the [Fe II] jet. No H_2 emission is detected near jets with older dynamical ages and driving sources that appear to be more evolved (e.g. HH 666, see [8, 5]). However, more evolved sources tend to be in more diffuse environments, raising the question of whether a source must be young (like HH 900) or embedded in a dense globule (HH 900, HH 901, HH 1066) to entrain enough molecules to survive an appreciable distance outside the globule in a region like the Carina nebula.

FIRE's $0.8-2.5$ μm wavelength coverage allows us to observe H_2 and multiple [Fe II] lines simultaneously. The observed offset of [Fe II] emission from the pillar edge is $\lesssim 2''$ in most sources, so mutually exclusive emission can be captured with FIRE's $7''$ slit. Measuring the Doppler velocities traced by [Fe II] and H_2 emission is essential to determine if they do, in fact, trace different components of the outflow. With FIRE, this can be done simultaneously. Multiple near-IR [Fe II] lines fall within FIRE's spectral grasp, including the density-sensitive ratio of the [Fe II] 1.64 μm/1.53 μm lines. Measuring the jet density as a function of position is also a critical test of the hypothesis that [Fe II] emission traces the jet and Hα emission traces the ionized skin of the entrained material. A sharply declining density along the jet axis away from the driving source may indicate large scale changes in the jet density with Hα emission predominately tracing the photoevaporative flow off the neutral jet core. In contrast, a steady jet with a relatively constant density, as appears to be the case with HH 900, suggests a recent jet outburst, where [Fe II] emission traces a jet that is still shielded from Lyman continuum photons by the not-yet ablated outflow sheath encompassing it.

The target list samples the full range of jet-driving protostar environments in Carina from small, dense globules (HH 1006), to translucent pillars (HH 903), to unobscured protostars (HH 1018). The proposed jets have also been targeted for [Fe II] imaging with WFC3-IR on *HST*. Complementing these images with spectroscopy allows us to measure the jet kinematics and disentangle the role of environment in producing the observed Hα and [Fe II] emission. Studying jets of similarly high mass-loss rate and velocity in different environments allows us to test whether the evolutionary stage of the driving source or density of the natal globule determines the amount of material entrained by the [Fe II] jet.

References

[1] Hartigan, P., Reiter, M., Smith, N., & Bally, J. 2014, AJ, submitted
[2] Pesenti, N., et al. 2003, A&A, 410, 155
[3] Reipurth, B. Yu, K.C., Heathcote, S., Bally, J., & Rodríguez, L.F. 2000, AJ, 120, 1449
[4] Reiter, M., & Smith, N. 2013, MNRAS, 433, 2226
[5] Reiter, M., & Smith, N. 2014, MNRAS, accepted
[6] Reiter, M., & Smith, N. 2014, in preparation
[7] Reiter, M., Smith, N., Kiminki, M., & Bally, J., 2014, in preparation
[8] Smith, N., Bally, J. & Brooks, K.J. 2004, AJ, 127, 2793
[9] Smith, N., Bally, J. & Walborn, N. 2010, MNRAS, 405, 1153

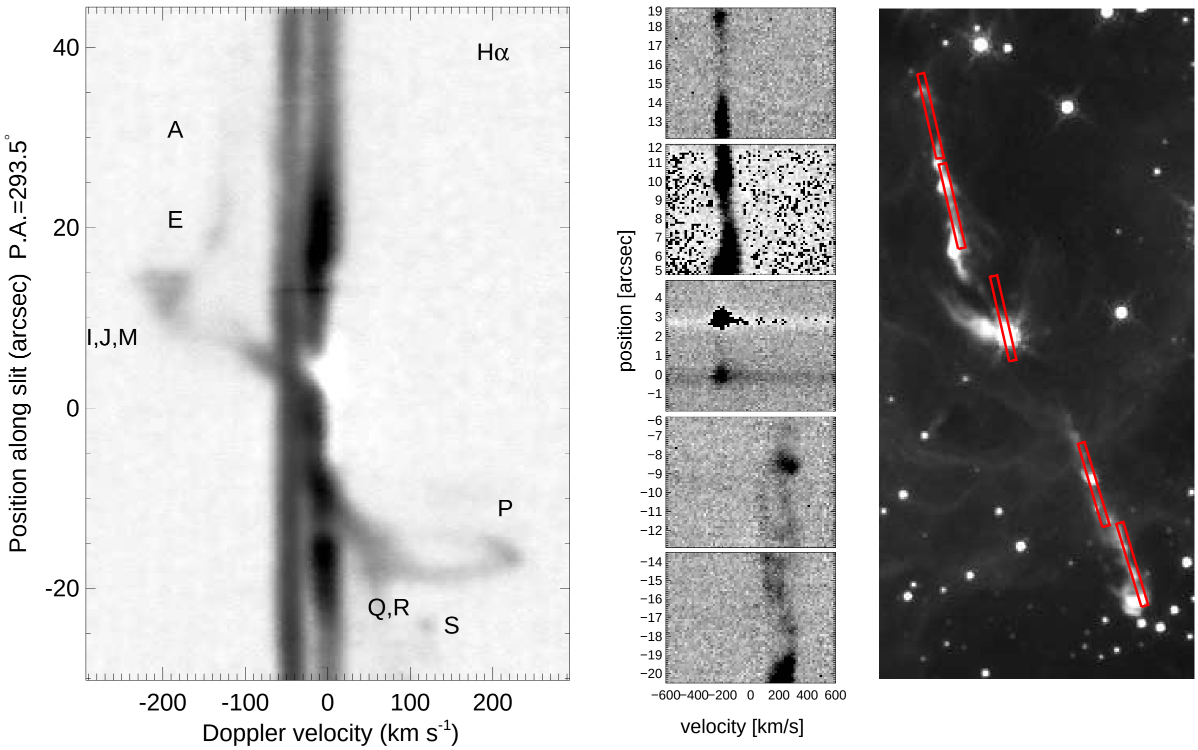

Figure 1: *Left*: Hα spectrum of HH 666 from [8]. Features HH 666 M and O expand in a Hubble-like flow in Hα emission. *Middle*: [Fe II] 1.64 μm spectra of HH 666 obtained with FIRE in 2013A tracing jet velocities of ± 200 km s^{-1}. There is no evidence for a decrease in velocity with increasing distance from the driving source as would be expected if [Fe II] was excited by shocks and not external FUV. *Right*: *HST* narrowband [Fe II] 1.64 μm image of HH 666 showing approximate FIRE slit positions.

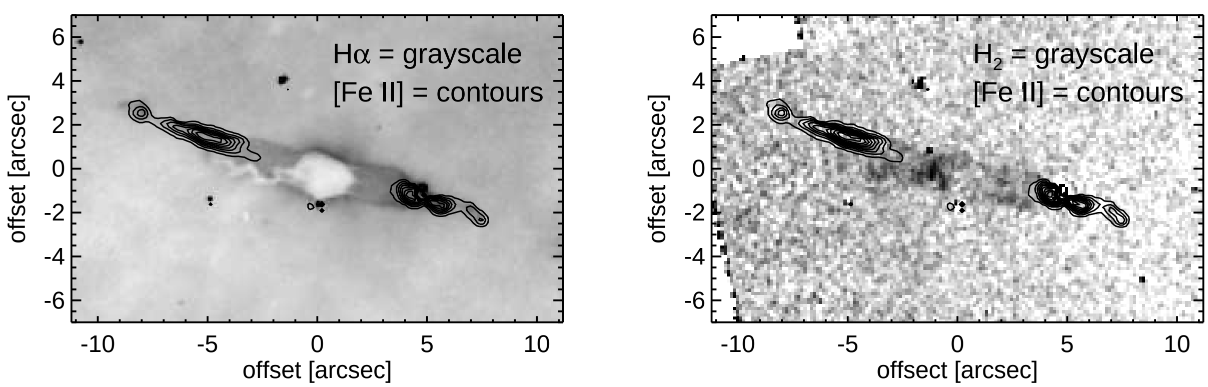

Figure 2: HH 900 in Carina exhibits both of the unexpected trends in P.I. M. Reiter's thesis survey of jets from intermediate-mass protostars. The Hα image from ACS/*HST* with contours of the [Fe II] emission from WFC3-IR/*HST* overplotted shown *Left* demonstrates the difference in morphology traced by the two emission lines. Position-velocity diagrams show the same velocity discrepancy observed in HH 666 (see Figure 1). HH 900 also has extended H_2 emission from the inner jet, as shown in the continuum-subtracted H_2 image of HH 900 from GSAOI shown *Right*. H_2 emission extends beyond the edge of the globule, but appears to end at the same place that bright [Fe II] emission begins (Reiter et al. 2014).

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)***

We propose to obtain near-IR spectra with FIRE of seven jets driven by intermediate-mass protostars in the Carina nebula using multiple pointings per jet over the course of three nights. The wide bandwidth available with FIRE ($0.8 - 2.5$ μm) allows us to simultaneously detect multiple near-IR lines of [Fe II], including the density sensitive ratio 1.64 μm/1.53 μm to determine the mass-loss rate in the jet and near-IR H_2. We will orient the slit along the axis of the flow in order to detect Doppler shifts of gas in the jet. This allows us to determine the outflow speed, jet orientation, and measure the physical properties of the [Fe II] and H_2 emitting gas in these jets. In these spectra, we also detect the two [Fe II] lines 1.26 μm and 1.64 μm. Both of these transitions arise from the same upper level, so their intrinsic flux ratio is determined by atomic physics. Therefore, the observed flux ratio can be used to estimate the reddening along the line of sight, providing another avenue to study the material entrained by the outflow.

The seven jets we propose to observe have similarly high mass-loss rates, but sample the environmental extremes of the Carina nebula ranging from the relative tranquility of the south pillars, to heavily irradiated environments a few pc from the many O-type stars of Trumplers 14 and 16. All of the proposed targets have or will have high resolution, narrowband [Fe II] images from an ongoing *HST* WFC3-IR program. FIRE's broad spectral grasp allows us to simultaneous measure the extent and kinematics of H_2 and [Fe II] emission. In addition, relatively steady velocities measured from [Fe II] jets provides an important constraint on the hypothesis that Hα emission traces irradiated ambient material that has been accelerated by the underlying [Fe II] jet.

Spectral resolution of ~ 50 km/s is well suited to detailed study of outflows with typical speeds of ~ 100 km/s. From sensitivity information on the FIRE webpage, and our experience observing other HH jets in Carina, we estimate that each jet pointing in the Carina nebula will require about ~ 60 minutes integration time (it varies from source to source and will be evaluated during the run). Thus, for our seven targets, we estimate that we need about ~ 25 hours of time, including calibrations and overheads.

We request 3 nights for this program, preferably during February or March, the optimal times to observe the Carina nebula.

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**)*

This is the fourth UAO proposal for P.I. M. Reiter's study of intermediate-mass protostars in the Carina nebula. Three half nights were awarded in 2012A and were used to conduct a pilot study of a few bright jet-protostar systems in Carina. Three additional half-nights were awarded in 2013A and 2014A to extend the sample to include a broader range of protostellar masses and jet strengths. Despite nearly a full night lost to poor weather, results from these earlier campaigns are either in press [5] or in preparation for submission later this fall [6, 7]. We request three additional nights in 2015A to test the impact of environment on the observed jet properties. Results will be compared to FIRE spectroscopy obtained on earlier runs in P.I. M. Reiter's thesis.

This project has made use of survey data from Hubble, Spitzer and Chandra as well as ground-based imaging from NEWFIRM and GSAOI in the near-IR. FIRE is the only high-resolution near-IR spectrograph in the southern hemisphere on a telescope large enough to sample the full dynamic range of IR emission from jets driving by intermediate-mass protostars at the distance of the Carina nebula.

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**)*

P.I. M. Reiter was awarded three half nights on FIRE in 2012A, 2013A, and 2014A. The first of the FIRE results have been accepted for publication in MNRAS (Reiter & Smith 2014), and two additional manuscripts are in preparation, with expectation that they will be submitted by the end of the year. Co-I N. Smith has observed with FIRE on Magellan previously to obtain spectroscopy of Luminous Blue Variables in the LMC and SMC. These spectra are currently being analyzed, but FIRE spectra from this run obtained to study the circumstellar material for a supernova were already included in a paper that is now accepted in AJ (Smith et al. 2011).