OBSERVING REQUEST
University of Arizona Observatories

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

Fe Contents of Fast-Moving Knots in the Cassiopeia A Supernova Remnant

P.I.: Bon-Chul Koo (SNU; *koo@astro.snu.ac.kr*; 82-2-880-6623)
CoI(s): Yong-Hyun Lee⋆ (SNU), Jae-Joon Lee (KASI)

Abstract of Scientific Justification

The supernova remnant Cassiopeia A provides a unique opportunity to observe the fine details of the explosion of core-collapse supernova. Dense, metal-enriched, fast-moving knots (FMKs) outlying beyond the main ejecta ring are from the innermost region and have crucial information about the explosion dynamics and explosion mechanism. We recently found a strong indication that the Fe abundances of these FMKs vary by more than an order of magnitude with some systematic trends that might be closely related to the explosion mechanism. This proposal is to perform spectroscopy of FMKs in order to confirm the variation of their Fe abundances. Our findings will give a new insight to the explosion mechanism of Cas A and core-collapse SNe in general. We request 5 hours of MMT (+MMIRS in MOS mode) bright time.

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/5	MMIRS	*		0.5	bright	Sep–Oct	Aug–Oct	yes	yes

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	CasA-E	23 23 56.43	+58 48 53.8	
2	CasA-W	23 23 08.45	+58 48 50.0	

Approval for Instrument Use from PI: See attached e-mail from Dr. Jinyoung Serena Kim.

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

The core-collapse supernova (CCSN) explosion is an outstanding problem in astrophysics. Despite considerable observational and theoretical progress, many issues remain unresolved, one of which is the formation of jet and its role in the explosion (e.g., Soker 2016, Fesen and Milisavljevic 2016).

Cas A is a nearby young (~ 340 yr) Galactic supernova remnant where we observe a distinct jet structure (Figure 1). It is a remnant of SN Type IIb with a probable progenitor mass of 15–20 $M_\odot$ (Krause et al. 2008). The spatial distribution of SN ejecta in Cas A is complex, manifesting the violent and turbulent explosion process. A most striking morphological feature is the northeastern 'jet' and southwestern 'counter-jet' extending far beyond the main ejecta ring. This spatially-confined jet structure is prominent in X-rays and is filled with diffuse Si-rich ejecta (Hwang et al. 2004). On the other hand, there is an extended X-ray plume filled with Fe ejecta outside the ejecta ring in the eastern area (Hwang and Laming 2012). The jet-counter jet structure implies a bipolar-type SN explosion, while the Fe-ejecta plume implies a low-mode convection in neutrino-driven explosion (DeLaney 2010, Wongwathanarat et al. 2013). A two-step explosion scenario to explain the both was also proposed (Burrow 2005). In optical images, numerous ejecta knots are visible in these areas (Figure 1). Optical spectroscopic studies have shown that these 'fast-moving knots (FMKs)' are dense S-rich and O-rich SN material (Hammell and Fesen 2008, Fesen and Milisavljevic 2016). The FMKs in the jet area are almost undecelerated, and they are thought to have been injected from the innermost region at the time of core collapse by an explosive, jet-like mechanism (Fesen and Milisavljevic 2016). But no Fe-rich ejecta knots expected in the jet-induced explosion models have been detected in the jet area so far (Khokhlov 1999, Fesen and Milisavljevic 2016).

We have recently obtained a long-exposure ($\sim$10 hr) image of Cas A by using the UKIRT 3.8-m telescope with a narrow-band filter centered at [Fe II] 1.644 μm emission (Figure 2; hereafter the 'deep [Fe II] image'). [Fe II] 1.644 μm line traces dense shocked atomic gas, and our deep [Fe II] image reveals the distribution of dense SN ejecta including FMKs. We have compared our deep [Fe II] image with the HST WFC3 F098M image (Fesen and Milisavljevic 2016) and found that essentially all FMKs in the [Fe II] image have counterparts in the HST F098M image but with different relative brightnesses. (The two images were obtained in different epochs, i.e., the deep [Fe II] image in 2013 September 4–14 and the HST F098M image in 2011 November 18, but we can compare them because we know the proper motion of these FMKs.) For example, in the NE jet area, the knots along the central stream is much brighter in the [Fe II] image than in the HST F098M image. As the HST F098M band is dominated by ionized sulfur lines, i.e., [S III] 0.907 μm, 0.953 μm, and [S II] 1.03 μm lines, the different brightness ratios indicate different Fe to S abundance ratios assuming that the shock conditions are comparable for these FMKs. Figure 3 is a plot of [Fe II] 1.644 μm/F098M flux ratios of the FMKs as a function of angular distance from the explosion center. The left frame is based on the observed fluxes while the right frame is based on the extinction-corrected fluxes. The extinction to Cas A is large and varies significantly over the field. We applied an extinction correction using Herschel 250 μm image. The extinction correction lowers the flux ratios systematically, but the trend remains the same. There are a few noticeable features. First, the flux ratios range almost three orders of magnitude, which implies a large variation in the Fe to S abundance ratio X(Fe/S). Second, FMKs in the eastern area (green squares) have high [Fe II] 1.644 μm/F098M flux ratios. Note that this is the area where diffuse X-ray Fe ejecta plume is. Dense Fe-rich knots embedded in diffuse Fe-rich ejecta appears to be consistent with small scale clumping and large scale anisotropy seen in recent 3-dimensional numerical simulations of neutino-driven SN explosions (Orlando et al. 2016). Finally, in the NE jet area (red squares), the farther FMKs have higher [Fe II] 1.644 μm/F098M flux ratios. This might indicate that the jet was launched in the Si-Fe layer, deeper than previsouly thought.

Our results in Figure 3 provide important clues on the explosion dynamics and explosion mechanism as described above. But it has caveats: (1) The deep [Fe II] image and the HST F098M image were obtained at different epochs, so that there is an inherent uncertainty in comparing their brightnesses. The brightnesses of the FMKs can change significantly on timescales less than one year (Fesen et al. 2011). (2) The extinction correction was done using a low-resolution ($18''$) far-infrared image. The extinction to Cas A is large (6–15 mag in A_V) and varies significantly over the remnant (Lee et al. 2015). (3) The comparison was made for line fluxes not for abundances. We need to know physical conditions to derive chemical abundances. (4) The

HST F098M image does not cover the entire SNR so that the flux ratios could have not been measured for FMKs in the southeastern area. This proposal is to improve these uncertainties and to confirm our findings by J- and H-band spectroscopy of FMKs using MMT-MMIRS in MOS mode. In the zJ+J band (0.94–1.51 μm), there are lines from S, P, and Fe, that can be used to derive the abundance ratios X(P/Fe) and X(S/Fe) (Koo et al. 2013). In the H-band, there is [Fe II] 1.644 μm line that can be used to obtain accurate extinction by comapring with [Fe II] 1.257 μm line (Koo et al. 2016). There are also many [Fe II] lines in these bands that can be used to derive physical conditions such as electron densities (Koo et al. 2016). Therefore, we can derive the extinction to individual FMKs and can derive reliable relative abundances of P, S, and Fe in each knot. Once we have abundances, we can compare them to the predictions in either jet-induced or neutrino-driven SN explosion models. Our results will shed light on what happens in the deepest inner region during the explosion of Cas A and core-collapse SNe in general. We propose two MOS pointings toward the eastern and western regions. Note that we can determine accurate slit positions based on the proper motions of FMKs. We request 5 hours of total observing time.

References

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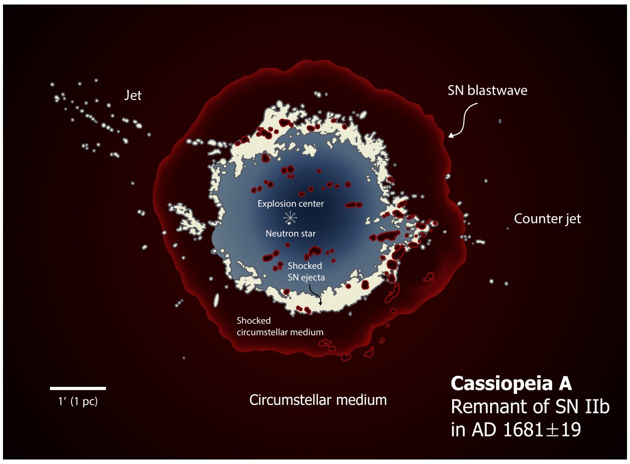

Figure 1: Schematic picture showing some essential features of the Cas A SNR. White and blue colors represent SN material, while red color represents the circumstellar mediim (Koo and Park 2017).

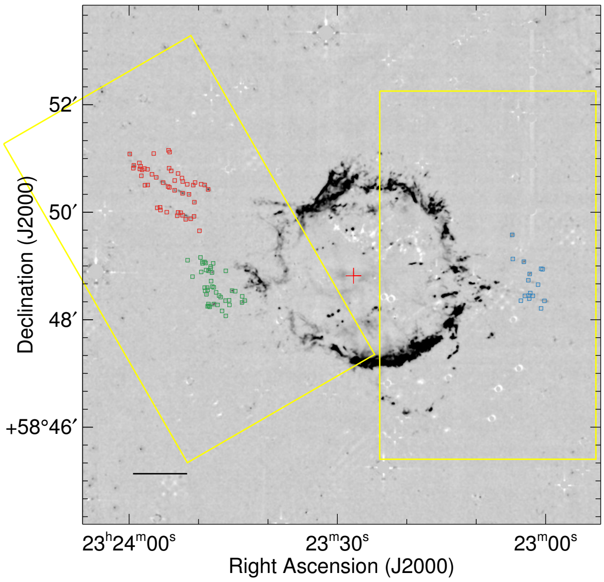

Figure 2: Long-exposure [Fe II] 1.644 μm image of Cas A obtained from the UKIRT 3.8-m telescope. Stellar sources have been removed. The red cross represents the explosion center. The scale bar in the lower left represents an angular scale of $1'$, which corresponds to 1 pc at the distance (3.4 kpc) of the SNR. The color-boxed FMKs are those in Figure 3. Two large yellow boxes mark the MOS fields for our proposed MMT MMIRS observation.

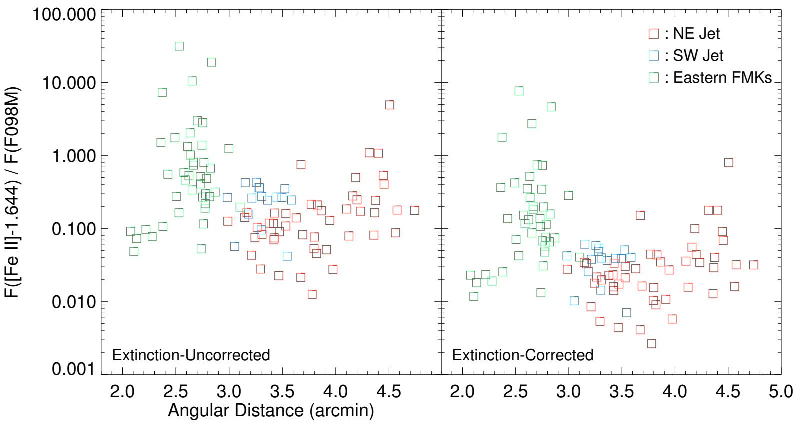

Figure 3: [Fe II] 1.644 μm to the HST FF098M band flux ratios of the marked ejecta knots in Figure 2 as a function of angular distance from the explosion center. The left and right frames show the extinction-uncorrected and extinction-corrected ratios, respectively.

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 a total of 2 MMIRS pointings in MOS mode to cover the NE+SE and SW jet regions where we found [Fe II]-bright fast-moving ejecta knots (Figure 2). The primary purpose of this proposal is to detect [Fe II] 1.257 μm and [S III] 0.9531 μm, [S II] 1.03 μm, [S I] 1.0824 μm, and [P II] 1.189 μm lines. So the zJ+J (filter+grism), which covers 0.94–1.51 μm, fits our purpose. We also wish to detect [Fe II] 1.644 μm line for the extinction correction. So we will use zJ+J and H+H3000 configuration for each pointing. The typical [Fe II] 1.644 μm brighness of FMKs is 1.5×10^{-16} erg s^{-1} cm^{-2} arcsec^{-2} when calibrated to 2MASS H-band photometry. Typical line width of [Fe II] 1.644 μm line of the FMKs is about 10 Å (200 km s^{-1}) (Lee et al. 2017), so for an aperture of $1'' \times 0.8''$ (knot size $\times$ slit width), the flux will be 1.2×10^{-13} erg s^{-1} cm^{-2} μm^{-1} which corresponds to 17.4 mag (Vega magnitude) around 1.644 μm. In the case of [S II] 1.03 μm multiplet lines, their brightnesses are 19.2 mag around 1.03 μm. Therefore, an exposure time of 30 min (1800 sec) yields $\sim$ 20 S/N for [Fe II] 1.644 μm and $\sim$ 10 S/N for [S II] 1.03 μm, respectively. For [Fe II] 1.257 μm lines, if we assume an extinction (A_V) of 8 mag, its expected brightness would be $\sim 8.4 \times 10^{-14}$ erg s^{-1} cm^{-2} μm^{-1}, which corresponds to 18.9 mag around 1.26 μm. We can obtain S/N of $\sim$ 10 for [Fe II] 1.257 μm with 30 min exposure. The 30 min on-source exposure time will be composed of 6 frames with 5 min-single exposure, considering the saturation of bright OH-airglow emission lines. As the jet regions are crowded with the ejecta knots, we need to observe a separate sky in order to subtract the sky background. Therefore, the observation will be "SKY–ON–ON–SKY–ON–ON–SKY–ON–ON–SKY" for each pointing with a single grism configuration. The total net-exposure time we request is therefore 3.3 hours, i.e., [30 mins + 20 mins (for sky)] $\times$ 2 pointings $\times$ 2 bands. Considering the overhead of target acquisition and instrumental setup, we request 5 hours for MMIRS time.

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 a new project.

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**)*

We used MMIRS in long-slit mode in 2016B for two nights to obtain the spectra of the interior emission of Cas A through the SAO time. We are currently analyzing the data.

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**)*

Gmail **Bon-Chul Koo <bckoo1420@gmail.com>**

MMT proposal

Jinyoung Serena Kim <jinyoungserena@gmail.com> Thu, Mar 30, 2017 at 8:03 AM
To: Bon-Chul Koo <koo@astro.snu.ac.kr>

Dear Bon-Chul.

Please go ahead with submitting the proposal.
I have heard from Brian McLead (the PI of MMIRS), YES.

Cheers,
Serena

> On Mar 29, 2017, at 6:54 AM, Bon-Chul Koo <koo@astro.snu.ac.kr> wrote:
>
> Dear Serena,
>
> It's been a while since we met in 2015 winter. I hope you have been well.
>
> This is about an MMT proposal. I am planning to submit a proposal to
> the K-GMT science program for using MMT MMIRS. According to my
> understanding, you are the contact person regarding the MMT proposal.
> I don't have a specific question related to the instrument at this
> point, but since MMIRS is a PI instrument, it seems that I need to get
> an approval from the PI through you. So I am sorry to rush you, but I
> am sending the title and abstract of my proposal for the PI approval.
> If you need more information, please let me know.
>
> title: Fe Contents of Fast-Moving Knots in the Cassiopeia A Supernova Remnant
>
> abstract: The supernova remnant Cassiopeia A provides a unique
> opportunity to observe the fine details of the explosion of
> core-collapse supernova. Dense, metal-enriched, fast-moving knots
> (FMKs) outlying the main ejecta ring are from the innermost region and
> have crucial information about the explosion mechanism. We have
> recently found a hint suggesting that the farthest FMKs are more Fe
> enriched, which, once confirmed, could give direct evidence supporting
> the jet-induced explosion. This proposal is to perform spectroscopy of
> FMKs to investigate their Fe-abundance. We request 5 hours of MMT
> (+MMIRS) bright time.
>
> Best wishes,
> Bon-Chul

E-mail from Dr. Jinyoung Serena Kim about the permission from the PI of MMIRS.