Supernova Remnants: An Odyssey in Space after Stellar Death – 2016 June

Near-Infrared Spectroscopic Study of Supernova Ejecta and Supernova Dust in Cassiopeia A

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1. Cassiopeia A SNR

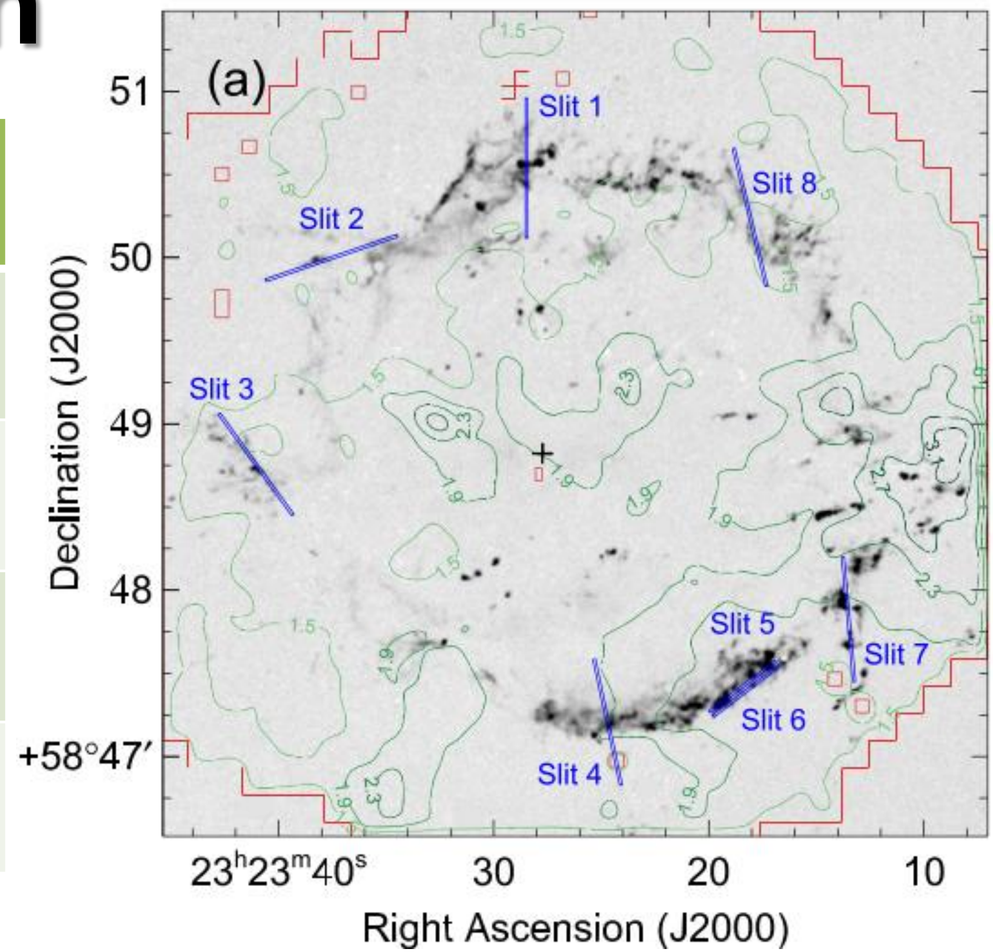
- **Cas A**: ~330 yrs old, Type IIb SNR at ~3.4 kpc
  => invaluable target to investigate the dynamics of SN ejecta and the freshly formed SN dust.

- For several decades, it has been extensively studied in optical waveband, but not much in near-infrared.
- Gerardy & Fesen 2001:
  => *JHK*-band spectroscopy for **8 optical knots** (5 FMKs + 3 QSFs) with low-spectral resolution (R~700)
  => FMKs are dominated by S, Si, whereas QSFs have strong He I 1.083um.

2. Observation

Observation Summary	
Instrument	**TripleSpec** @ Palomar 5-m
Band Coverage	**0.94 ~ 2.4 um, simultaneously**
Resolving Power	**~3,000**
Date	June, 2008

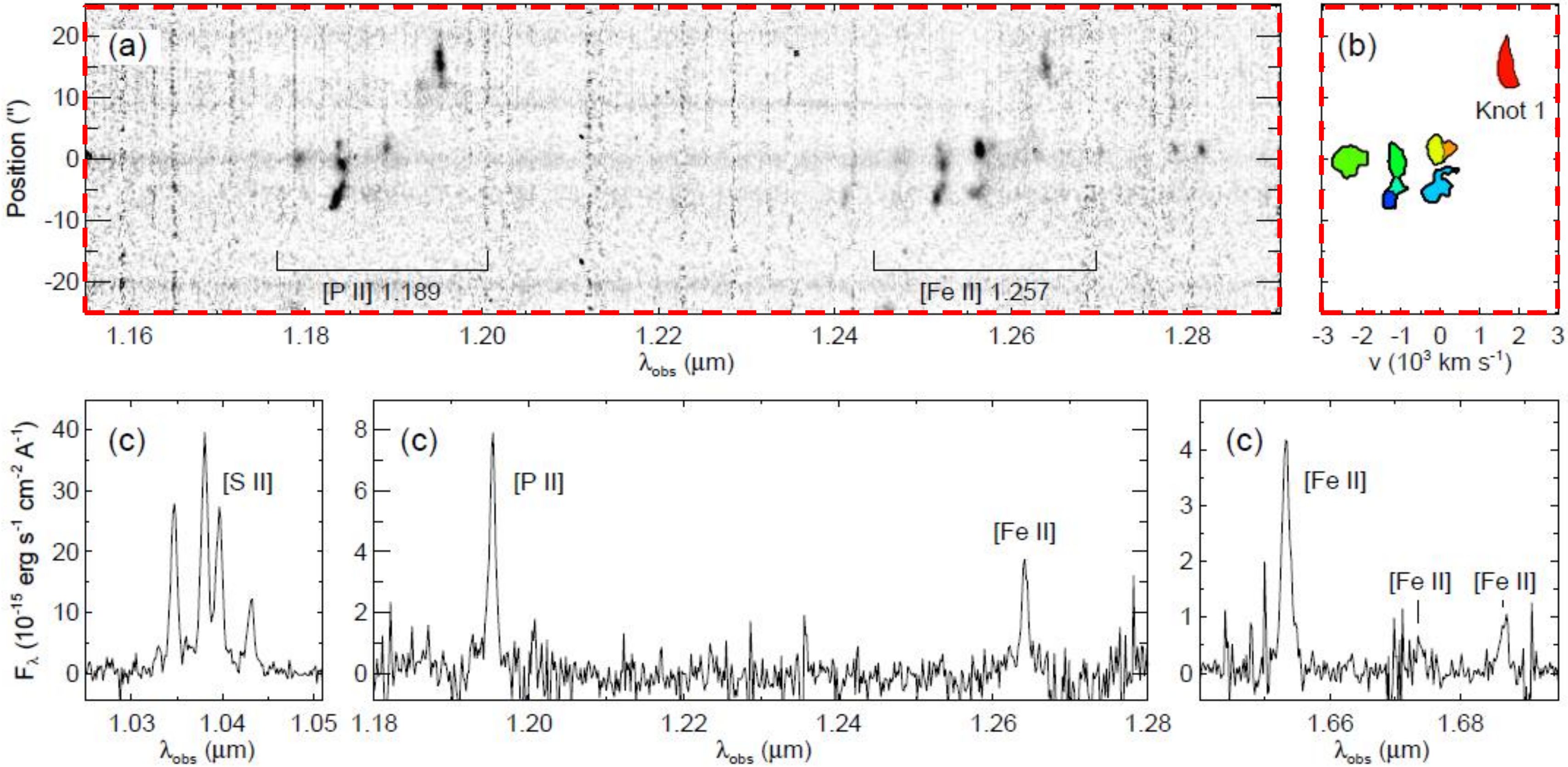
* Continuum-subtracted
[Fe II] 1.64um narrow band image



■ We obtained the NIR spectra of **8 slit positions** toward the main ejecta shell

3 Knot Identification

* 2D spectrum of H-band in Slit1 * Template image

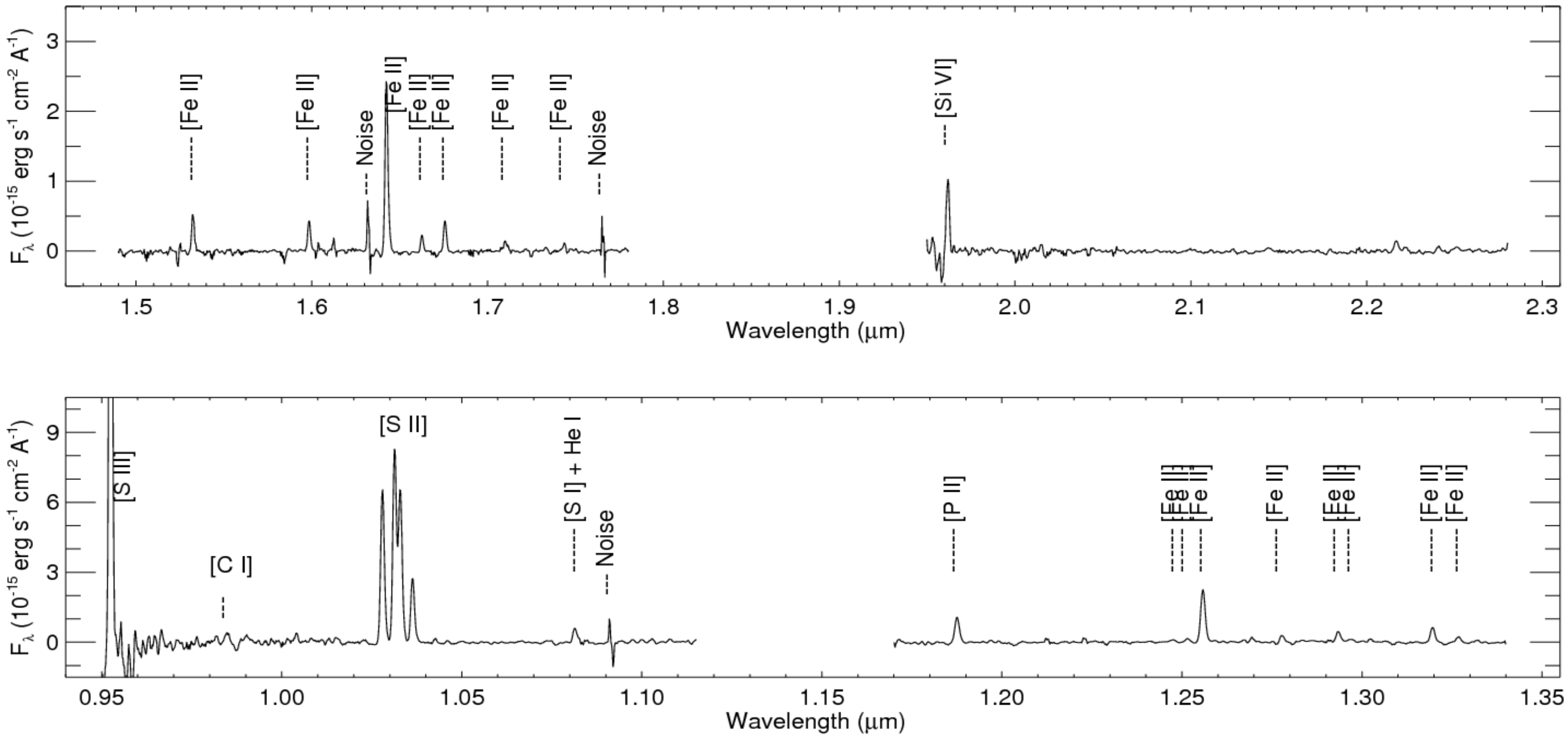


Koo et al. 2013

■ **63 individual knots**, in total, were identified from Clump-finding algorithm (*CLUMPFIND* IDL routine).

4. Line Identification

* 1-D spectrum of Knot 3 in Slit3



■ **A total of 46 emission lines**: **H / He recombination lines**, **forbidden lines from oxygen burning materials** (e.g., [Si VI], [P II], [S II], [S III]) and from neutral atoms ([C I], [N I], [Si I], [S I]), and **plenty of ionized iron lines** ([Fe II], [Fe III])

5. Two Topics

A. Spectral Classification of SN ejecta

=> Investigate **the origin of the NIR knots.**

B. Extinction toward the Cas A

=> Report the detection of self-extinction

=> Find the **composition of cool SN dust**

A. NIR Spectral Classification of Knots in Cas A SNR using PCA Method

(Spectral Classification of Ejecta)

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A-1. Importance of Classification

■ Classification in previous **optical studies**.

(1) Kinematic classification

=> FMKs (SN ejecta), QSFs (CSM)

(2) Chemical classification (Hammell & Fesen 2008)

=> O-rich, N-rich, S-rich knots (outer knots)

■ **Purpose of this study**

=> Perform Spectral classification using **NIR spectroscopy.**

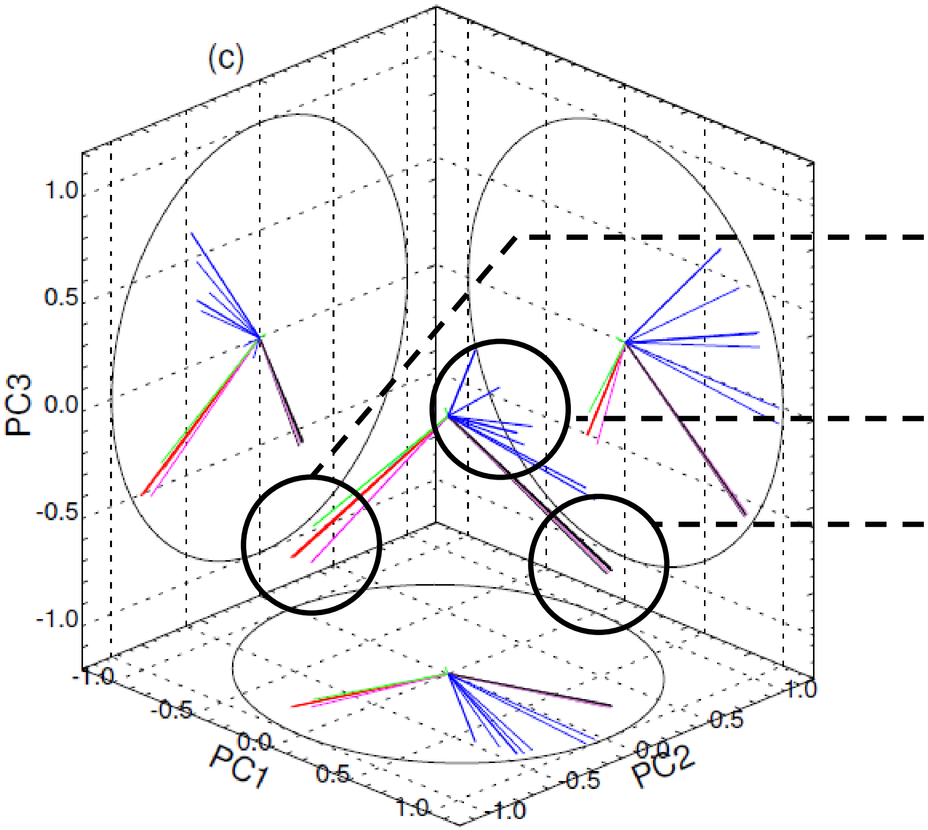
=> Investigate the origin of the NIR knots.

A-2. PCA Result

- **Principal Component Analysis (PCA)**

  => characterize the spectral data using a few PCs

  => first three PCs: more than 80% of information



* Emission lines in 3-D PC space

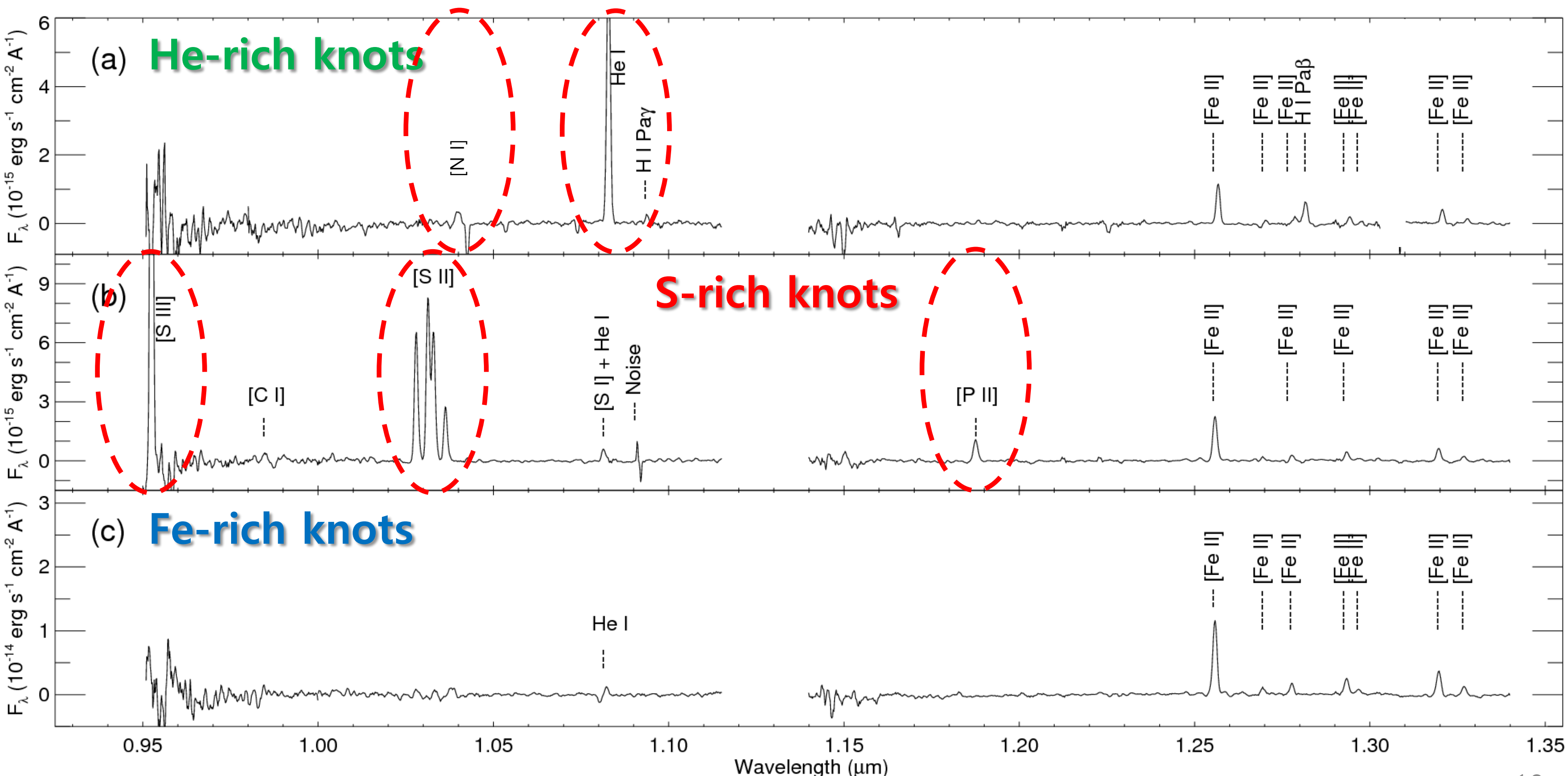
< 3 Groups of Lines >

- **Group 1**: [Si IV], [P II], [S I], [S II], [S III]
- **Group 2**: [Fe II], [Fe III]
- **Group 3**: H I, He I, [N I]

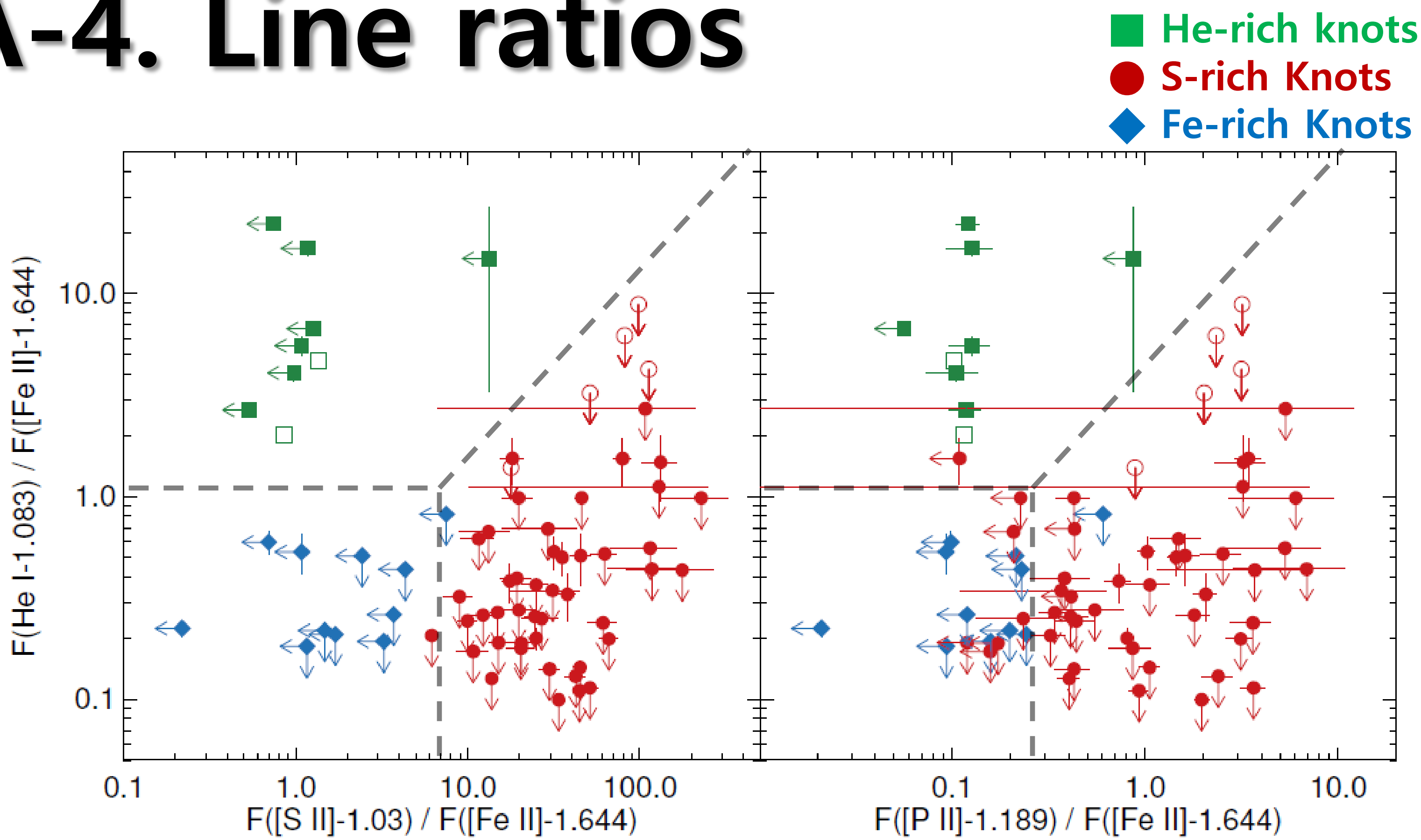
=> The emission lines in each group show (strong) correlation.

A-3. Three groups

■ One-D spectra of three major groups

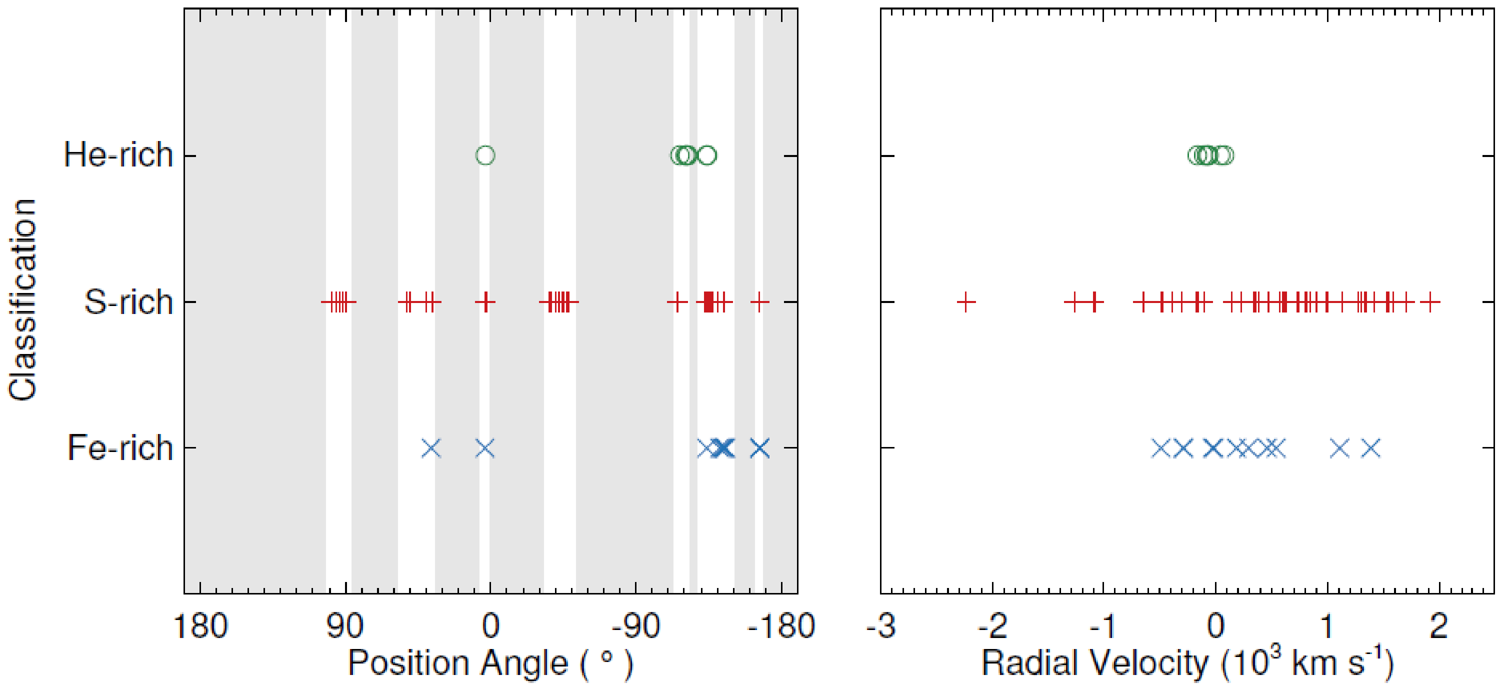


A-4. Line ratios



- The three groups are also (well) separated in the flux ratios of He I 1.08 μm, [P II] 1.19 μm, [S II] 1.03 μm, and [Fe II] 1.64 μm, four strong lines in NIR regime.

A-5. Characteristics



■ S-rich knots are detected in all slit positions, while He- / <u>Fe-rich knots are mostly detected in SW</u>.

■ Vr of the S-rich, Fe-rich knots goes up to a few 1000 km/s, while the He-rich knots have only less than ±200 km/s.

A-6. Origin of NIR Knots – (1)

■ Helium-rich knots

(1) strong He I, H I, [N I] w/o Si, P, S

(2) low $|v_r|$ of 200 km/s

=> consistent with those of QSFs

 # Dense Circumstellar Medium~!

■ Sulfur-rich knots

(1) Strong lines of oxygen burning elements ([Si VI], [P II], [S II], [S III], …), w/o H I lines

(2) high $|v_r|$ up to 2000 km/s

=> consistent with those of FMKs

 # SN Ejecta from Oxygen burning layer

A-6. Origin of NIR Knots – (2)

■ Iron-rich knots

(1) strong [Fe II] with weak He I w/o H I, [N I]
(2) v_r range is similar to S-rich knots (FMKs)
=> different from those of optical knots (FMKs, QSFs, FMFs(NKs))

(3) Two possibility for the origin - (1)

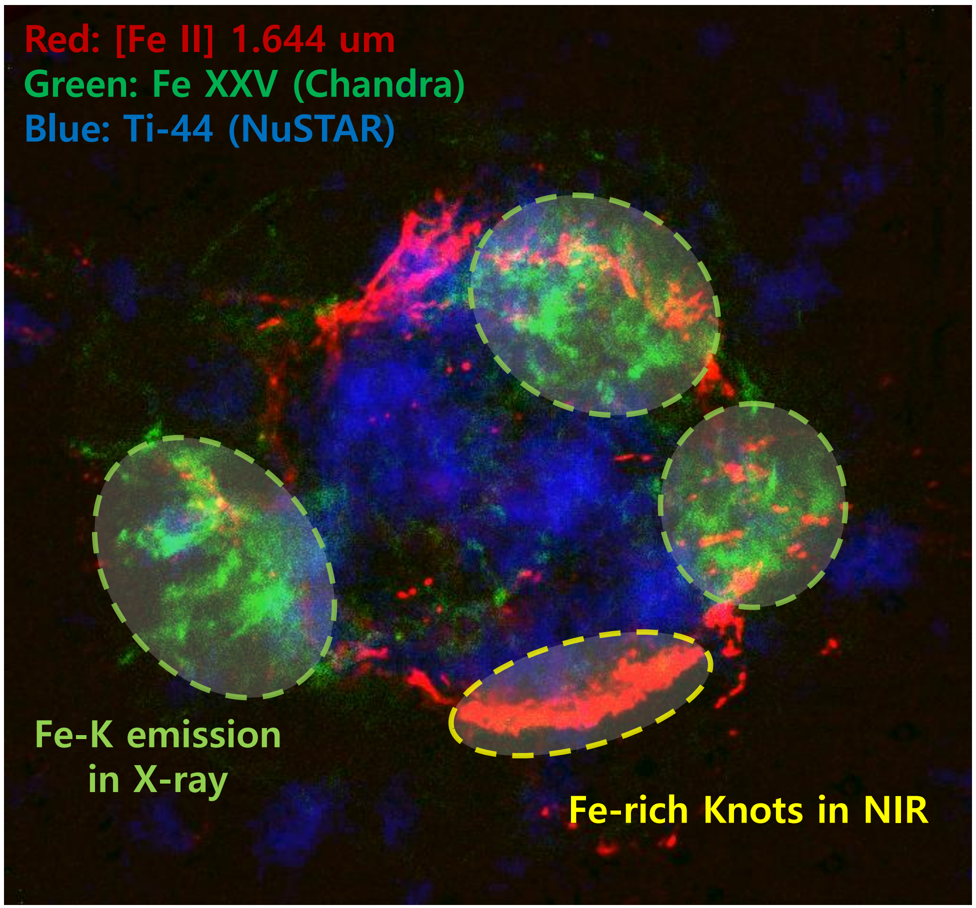
1. CSM around contact discontinuity?

=> explain the high speed around the shell
=> difficult to explain the absence of H I and [N I] lines...

A-6. Origin of NIR Knots – (3)

(3) Two possibility for the origin - (2)

2. SN Ejecta from the innermost layer?



⇒ **Fe-rich knots in NIR**: mostly detected in SW shell

⇒ **Fe-K ejecta in X-ray**: located N, W, SE of the remnant.

⇒ Need additional NIR spectroscopy toward the entire remnant...

B. Near-Infrared Extinction due to Cool Supernova Dust in Cassiopeia A (Composition of Cool Dust)

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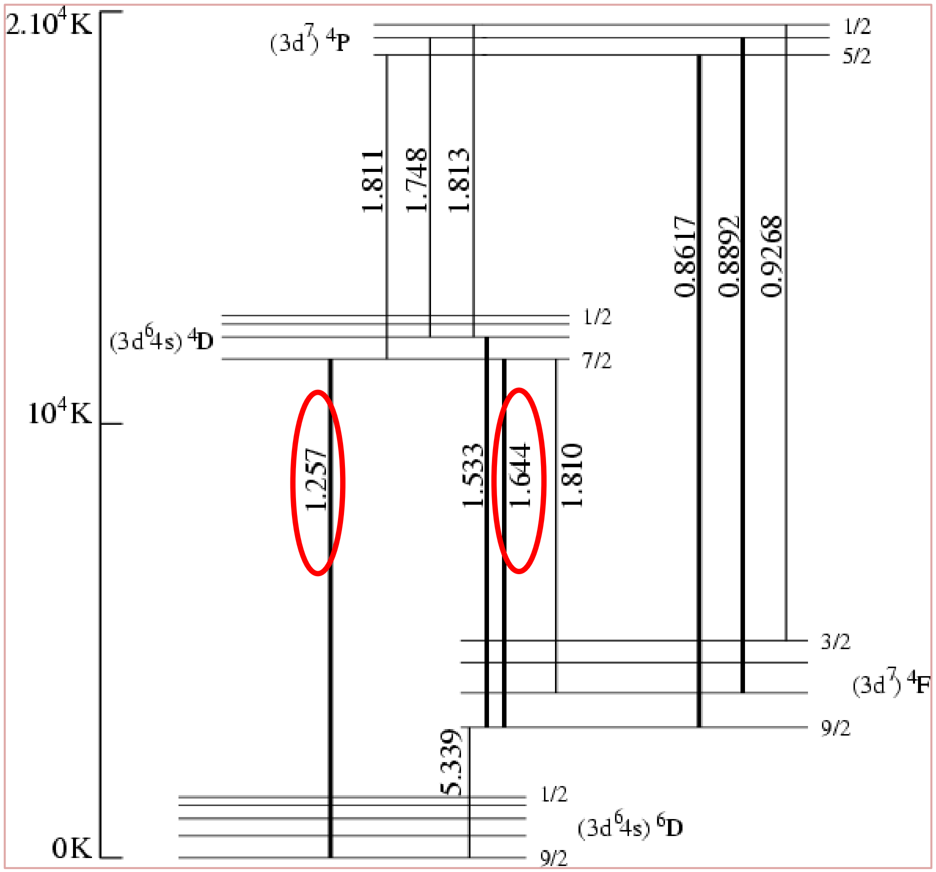
B-1. [Fe II] Lines in NIR

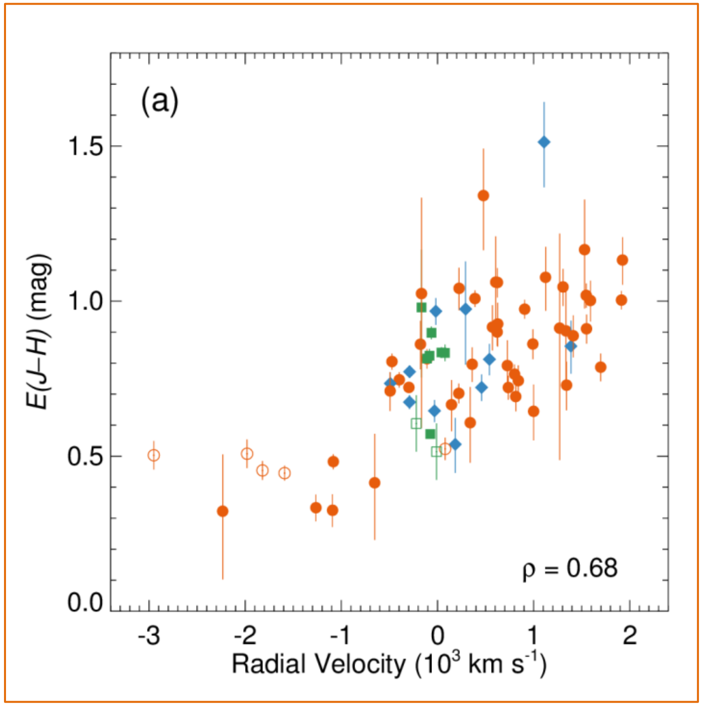


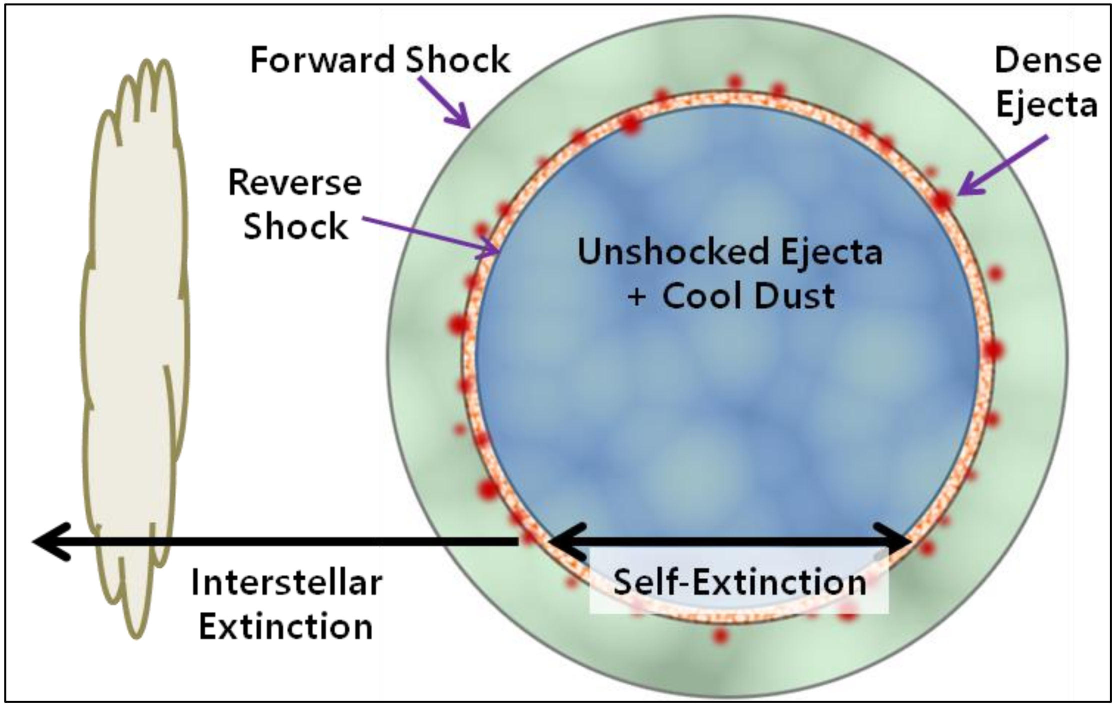
Pesenti et al. 2003

- The two strong [Fe II] lines located at 1.26 and 1.64 um share the same upper state ($a^4D_{7/4}$).
  => **Extinction indicator**

$$E(J-H) \equiv A_{1.26} - A_{1.64} = 1.086 \ \ln \frac{[F_{1.26}/F_{1.64}]_{\rm int}}{[F_{1.26}/F_{1.64}]_{\rm obs}},$$

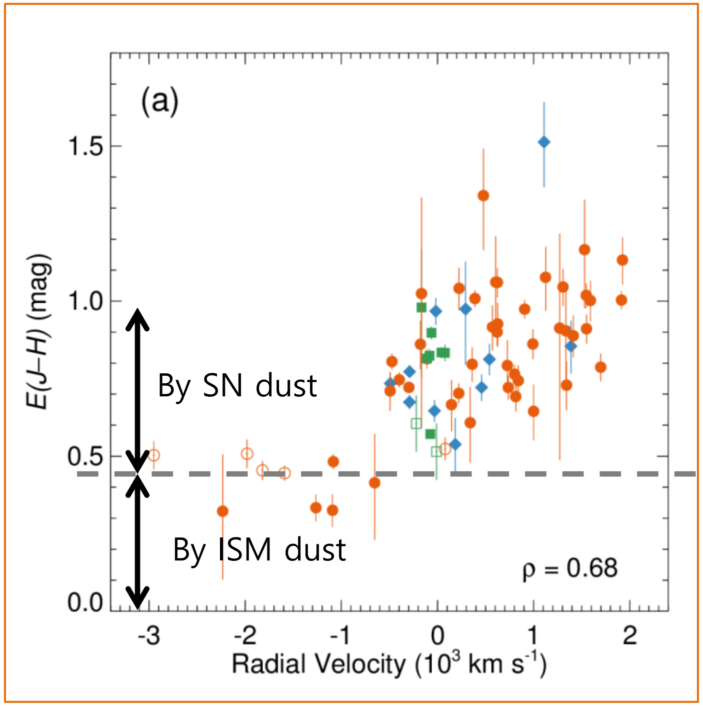
B-2. Extinction by SN Dust

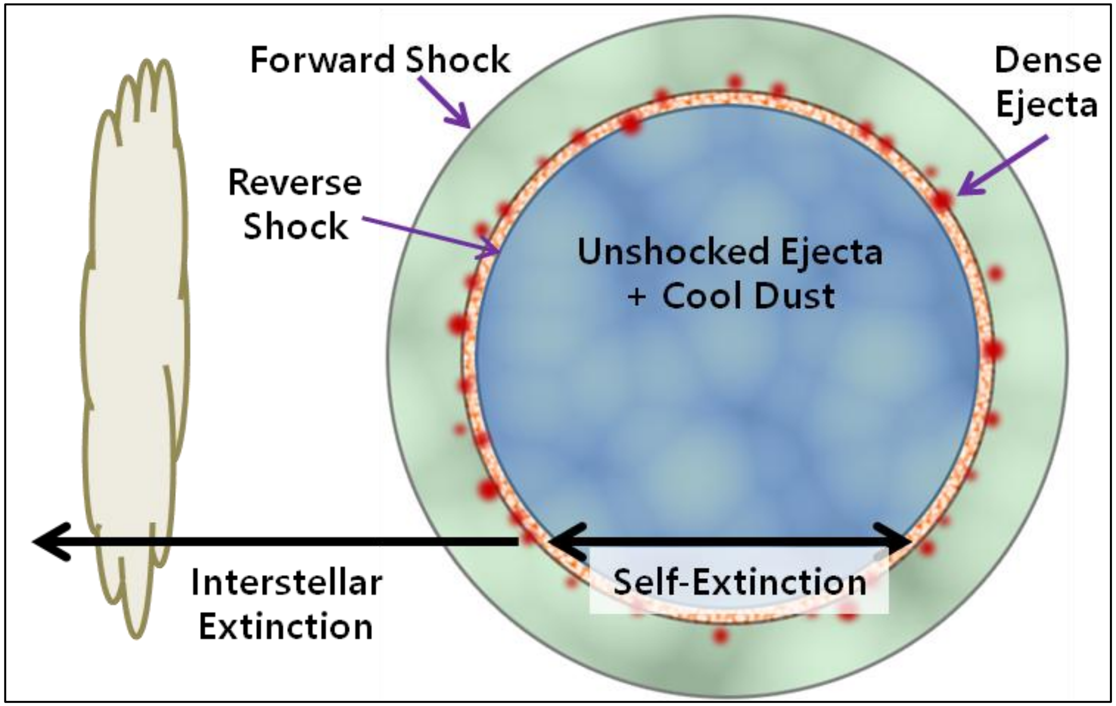




- Apparent correlation between *E(J-H)* and radial velocity
  => Extinction difference between front-side and back-side ejecta knots
  => **<u>'Self-Extinction' by the SN dust</u>** inside the remnant

B-2. Extinction by SN Dust





- Apparent correlation between *E(J-H)* and radial velocity
  => Extinction difference between front-side and back-side ejecta knots
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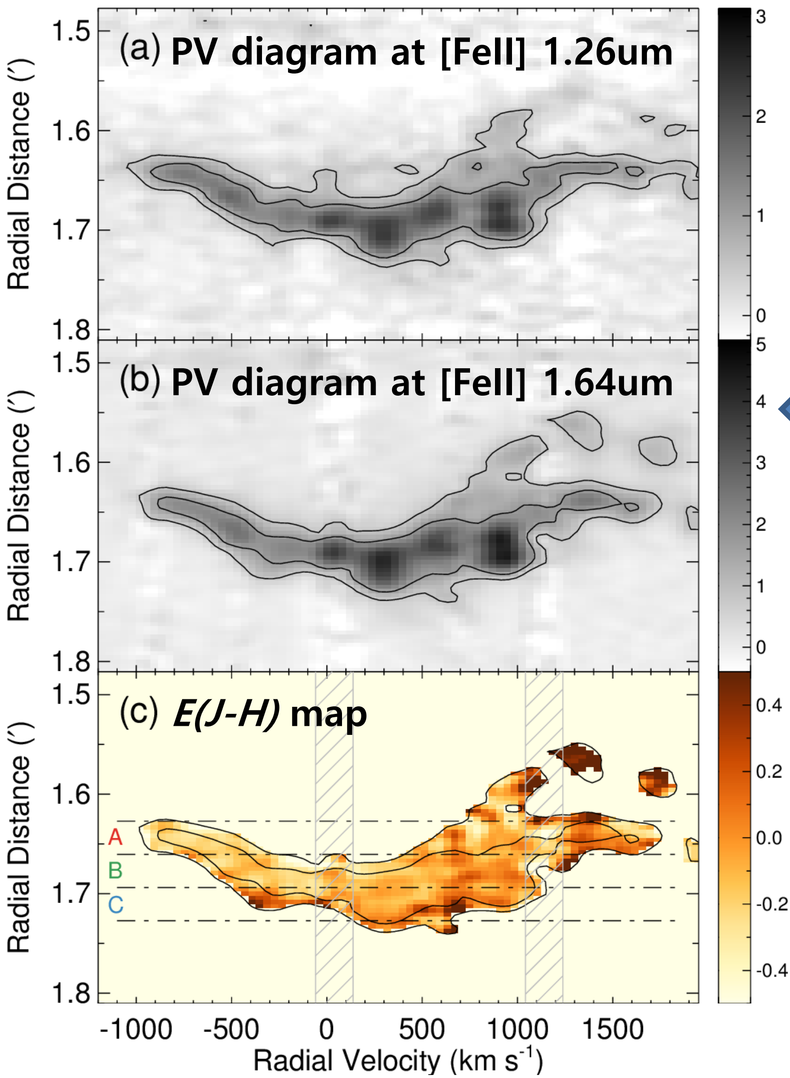
B-3. Self-Extinctio



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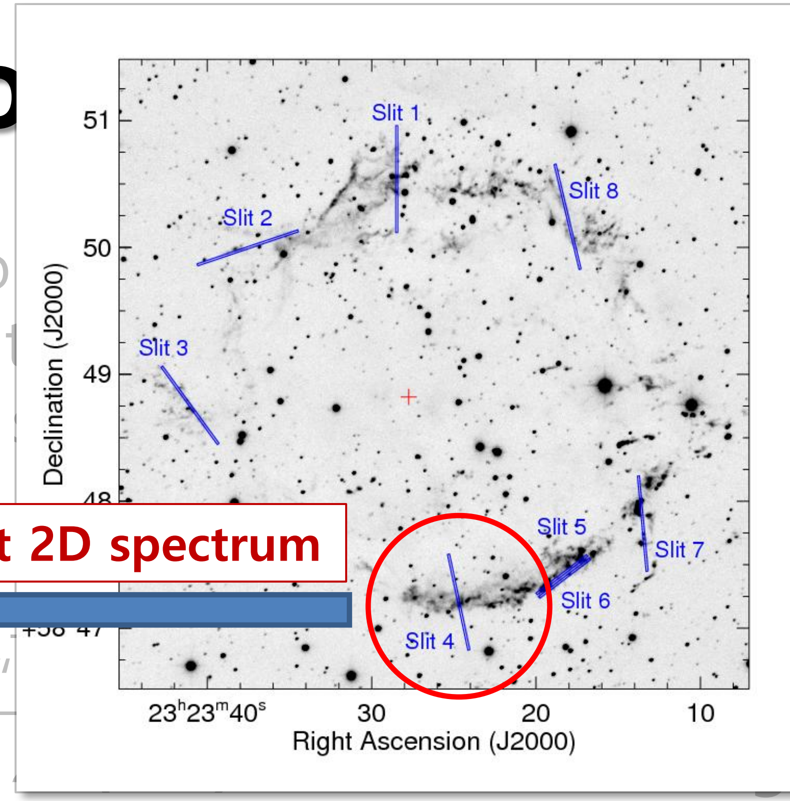
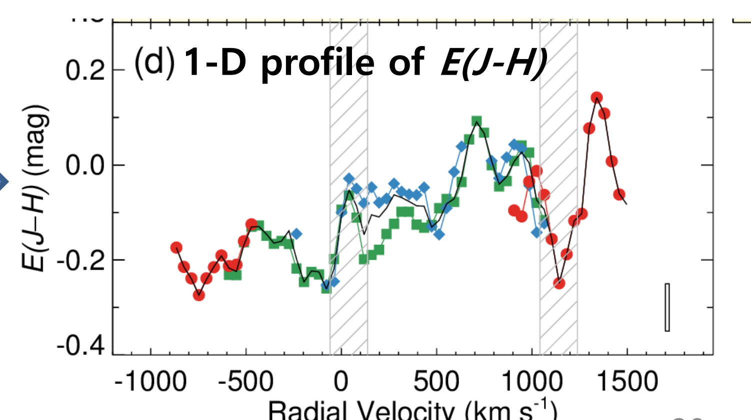
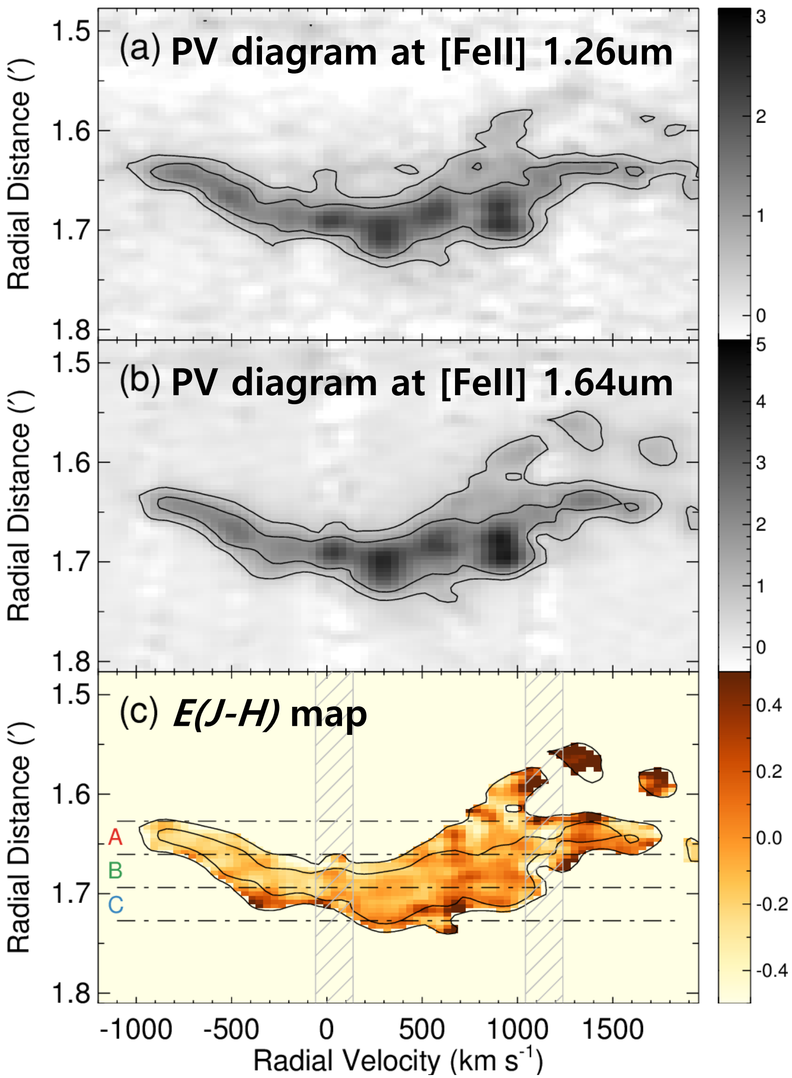


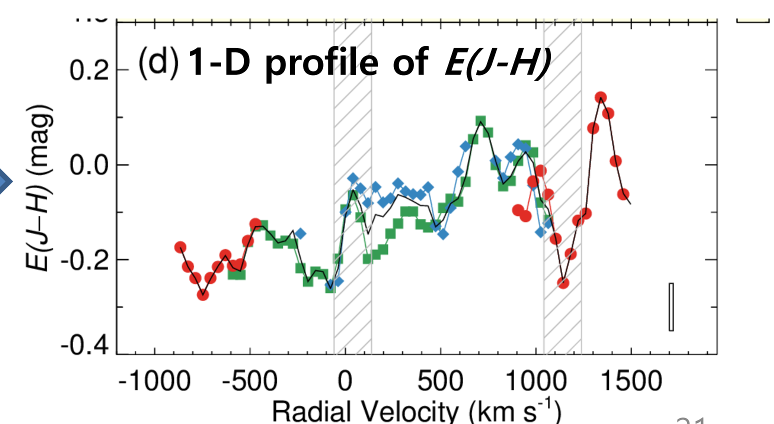
Extract 2D spectrum



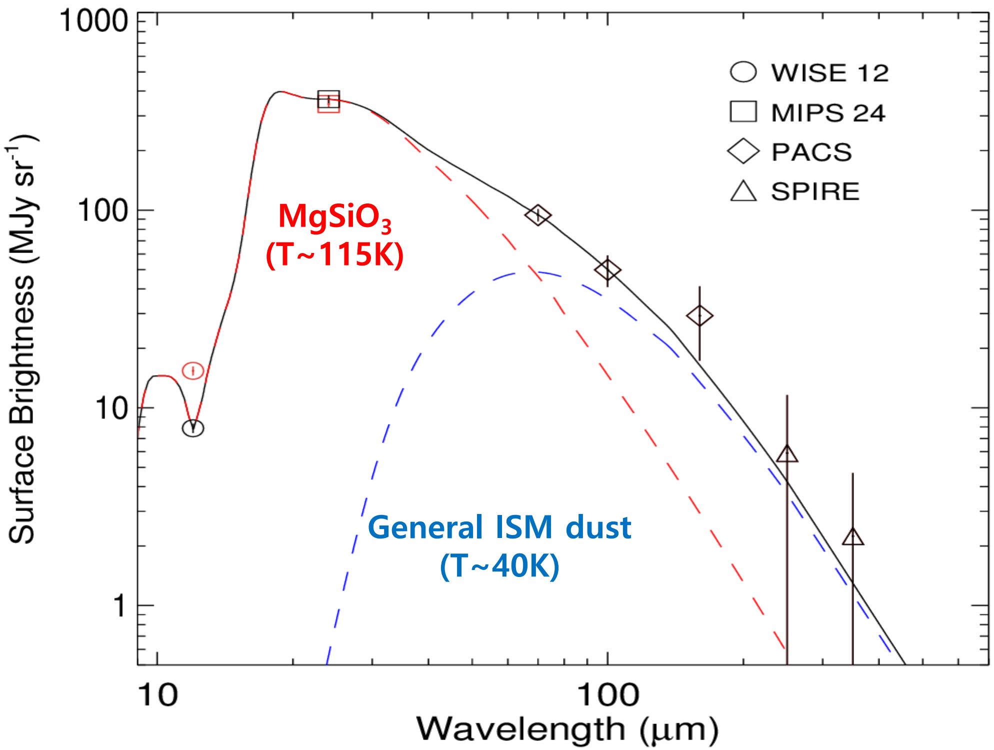
B-3. Self-Extinction



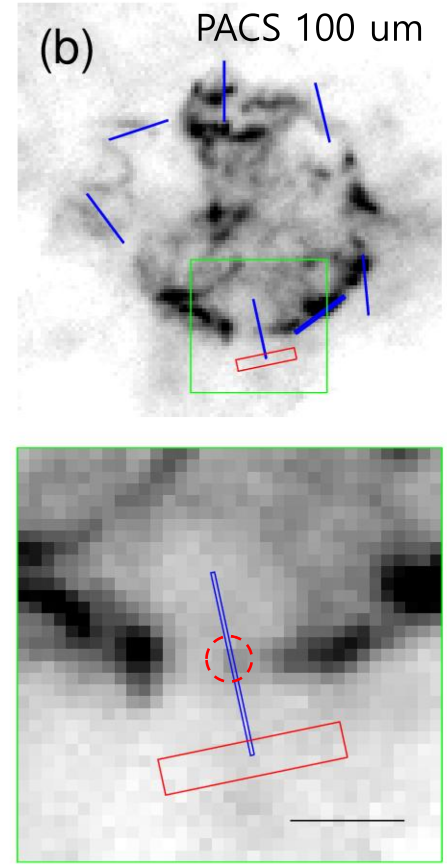
- "Iron-shell" in Slit 4: continuous structure along v_r => suffer same ISM extinction
- Clear variation of *E(J-H)* => <u>convincing evidence for "Self-extinction" !</u> => ***ΔE(J-H)* = 0.23±0.05 mag**



B-4. Warm Dust



after subtracting background SED



■ MIR dust emission: The warm dust should be **$MgSiO_3$, Mg_2SiO_4, and SiO_2** in order to explain the sharp 24um peak.

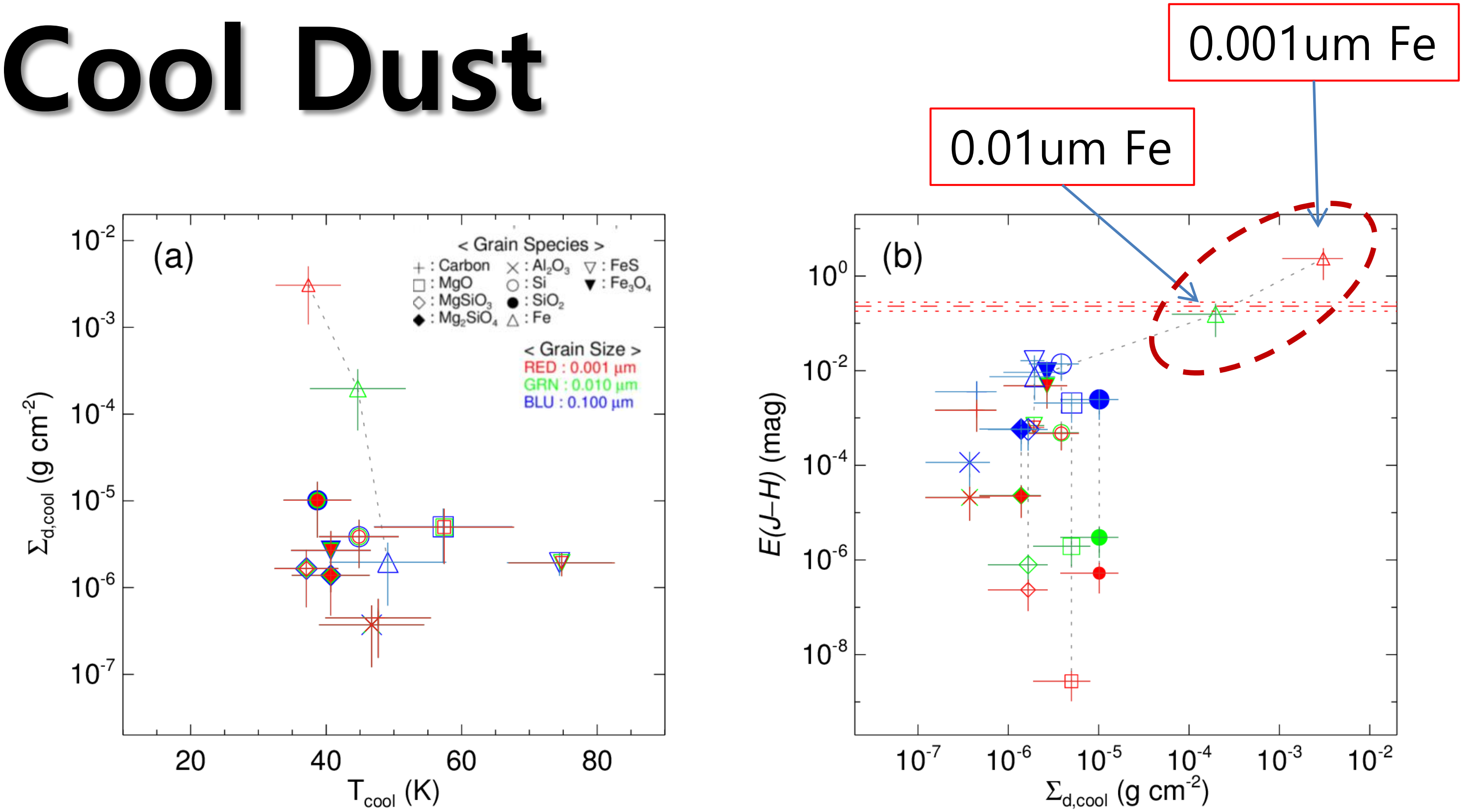
■ Color excess: 10^{-8} mag < ***E(J-H)*** **< 10^{-4} mag**

=> CANNOT be responsible for the self-extinction

=> Most of E(J-H) we observed is arising from the cool dust ???

B-5. Cool Dust

* Case where the warm dust is $MgSiO_3$



■ **small (a<0.01um) Fe grain** can explain E(J-H)>0.2 mag

■ When if the grain size is larger than 0.1 um

=> **large (a>0.1um) Si grain** also gives E(J-H) > 0.2 mag

B-6. Conclusion

■ **Two possible cool dust grain species**

1) small (a < 0.01um) Fe grain

2) large (a > 0.1um) Si grain

=> **Expected in inhomogeneous & clumped ejecta** (Sarangi & Chechneff 2014, Nozawa et al. 2015)

■ **Warm dust of Silicate v.s. Cool dust of Si/Fe**

=> the grain species in diffuse material and dense clumps are different, i.e. **silicate grains in diffuse ejecta material** and **small Fe or large Si grains in dense clumps**.

(A) Lee, Y.-H. et al. 2016, in prep.
(B) Lee, Y.-H. et al. 2015, ApJ, 808, 98

< Summary >

■ **Near-infrared study is also useful to investigate the dynamic of SN ejecta and the freshly formed SN dust.**

1. Spectral Classification of SN Ejecta

■ 3 major groups in NIR: **(1) He-rich, (2) S-rich, (3) Fe-rich knots**.

■ He-rich and S-rich knots are identical to QSFs and FMKs, respectively.

■ The Fe-rich knots seems to be either **CSM around contact discontinuity** or **pure iron core ejecta.**

2. Composition of Cool SN Dust

■ The self-extinction at Slit 4 (SW shell) is **E(J-H)~0.2 mag**.

■ Two possible solutions of the cool dust grain in SW:
(1) small (<0.01um) Fe grains or **(2) large (>0.1um) Si grains**.

■ We suggest that **the unshocked SN ejecta is clumpy**