Physical conditions in dense molecular knots in the supernova remnant Cassiopeia A

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Dust in supernovae

- Large dust masses seen in galaxies at $z > 6$
  - $M > 10^8\ M_\odot$ [(1)]
- Short timescale to produce this dust
  - Supernovae!
- But only small amounts of dust seen a few years post-SN
  - 10^{-5} to $10^{-2}\ M_\odot$ from IR observations[(2)]
  - Predictions of 0.1 to 1 $M_\odot$ per SN[(3)]

[(1)]Bertoldi et al. 2003
[(2)]e.g. Lucy et al. 1989, Sugerman et al. 2006
[(3)]e.g. Todini & Ferrara 2001, Cherchneff & Dwek 2010

Dust in supernova remnants

- Larger cold dust masses in SNRs
  - About 0.1 $M_\odot$ in Cas A[1]
  - 0.4 to 0.7 $M_\odot$ in SN87A[2]
- But not yet reprocessed by the reverse shock
  - Shock velocity ~1000 km/s
  - Models estimate dust destruction up to 100%[3]

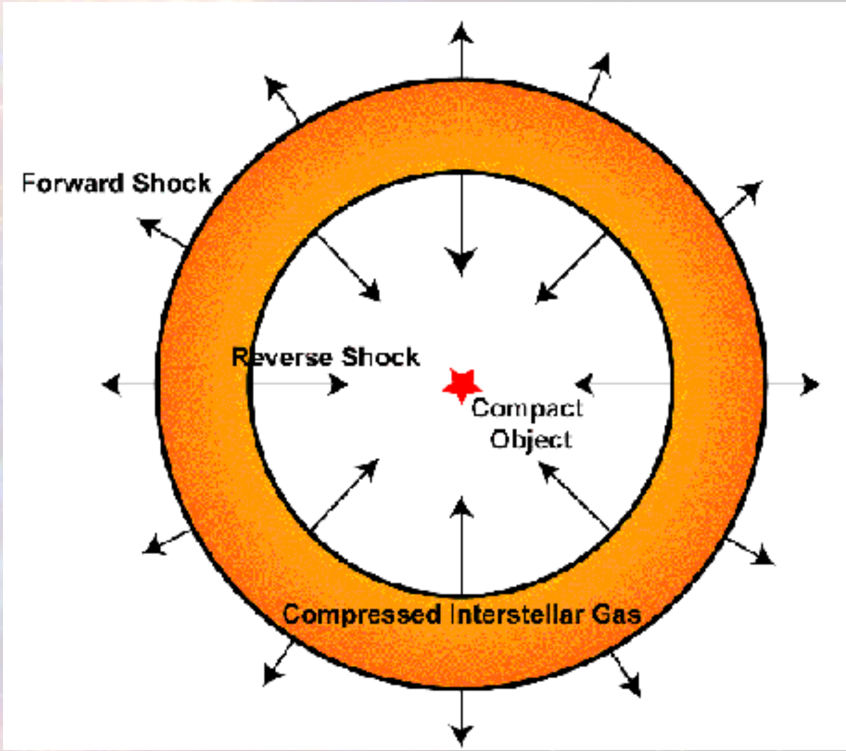


Image credit: NASA's HEASARC

(1)Rho et al. 2008, Barlow et al. 2010
(2)Matsuura et al. 2011
(3)e.g. Nozawa et al. 2007

Dense ejecta knots

- Rayleigh-Taylor instabilities following SN explosion
  - Ejecta highly inhomogeneous: dense knots
- Dense knots promote formation of molecules and dust growth
  - High density also slows reverse shock
  - ~200 km/s shock does limited damage to dust[1]

[1] Jones et al. 1994, 1996

Cassiopeia A

- 330 years old SNR
- Distance 3.4 kpc
- Large dust masses
  - 0.025 $M_{\odot}$ warm dust[1] associated with reverse shock
  - 0.075 $M_{\odot}$ unshocked cold dust[2]

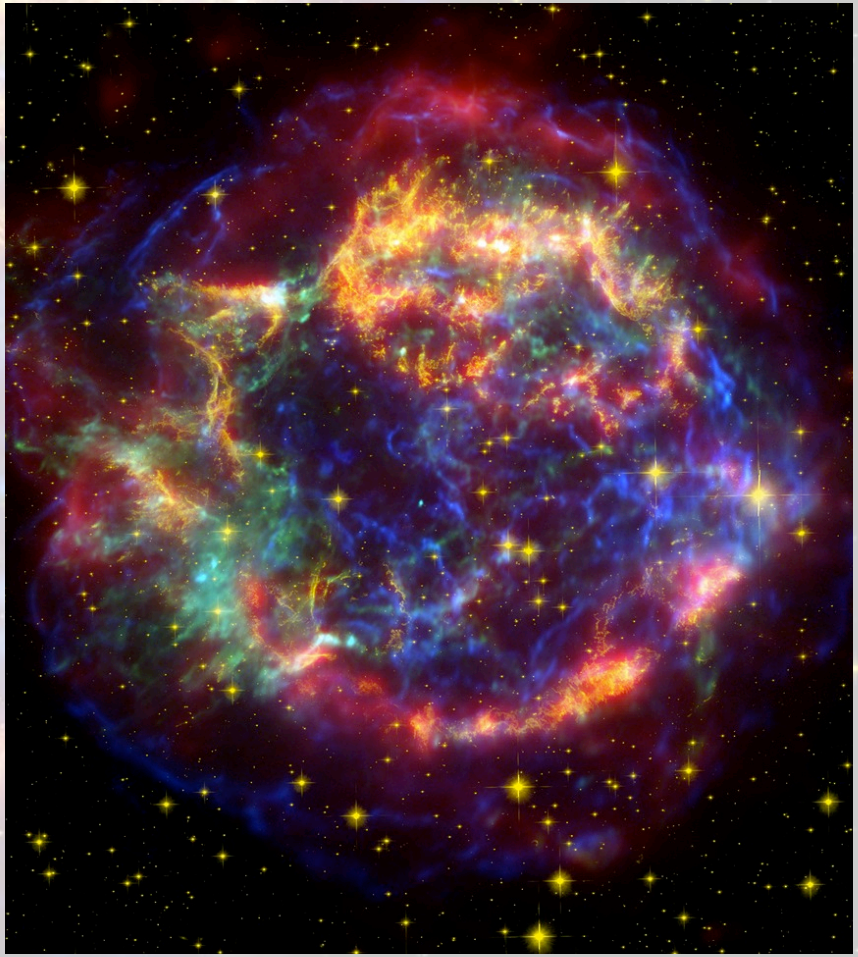


Image Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

[1]Rho et al. 2008
[2]Barlow et al. 2010

Cassiopeia A

- Ro-vibrational CO detected[1]
  - In many small (<0.8") knots
  - Coincident with reverse shock
- Difficult to derive physical conditions

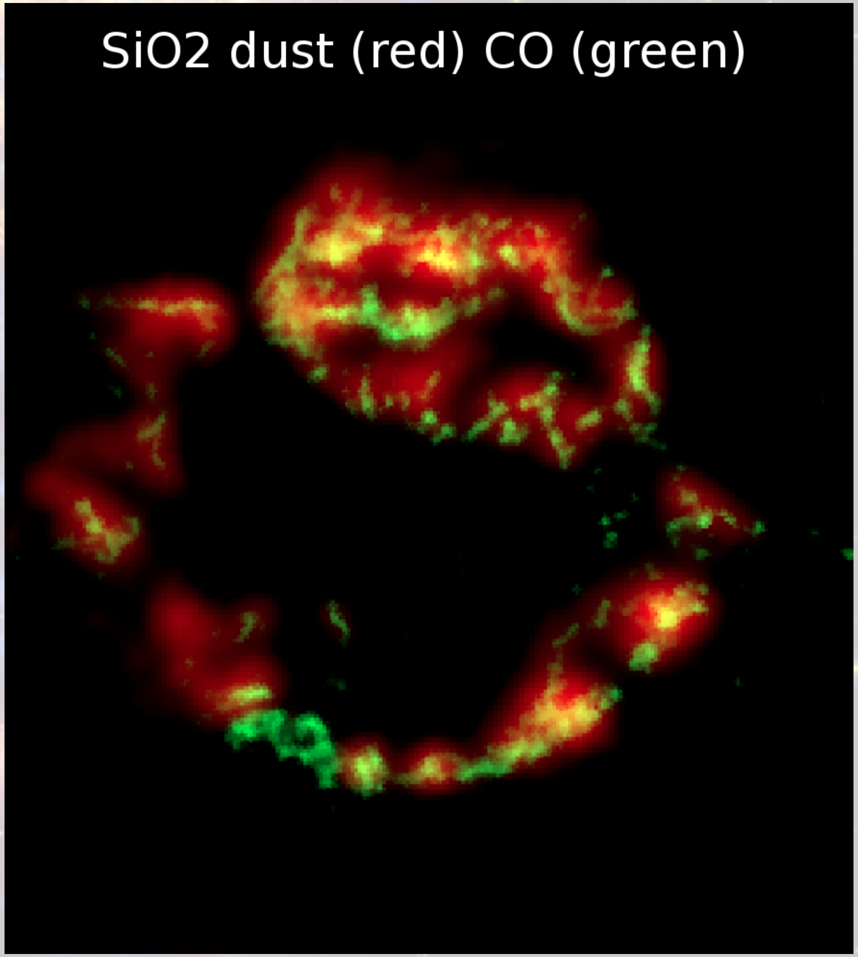
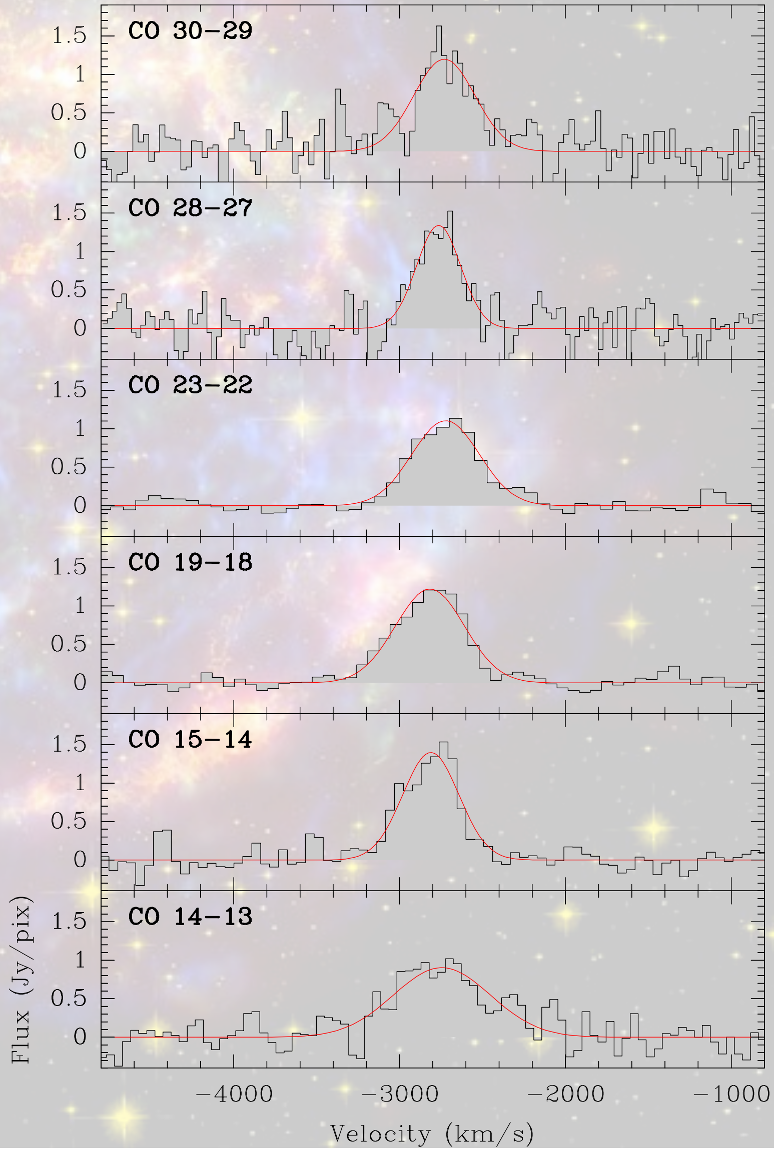


Image credit: J. Rho

[1] Rho et al. 2009, 2012

Herschel PACS observations

- Brightest CO knot targeted in several rotational CO lines[1]
- Blueshift of -2800 km/s
- Broad lines ~400 km/s
- Physical conditions:
  - Large column density (10^{19} cm^{-2})
  - Dense (10^5 to 10^6 cm^{-3})
  - Warm (500-1000 K)



[1]Wallström et al. 2013

CO knots in Cas A

- CO most likely in post-reverse-shock region
- Large column density of warm gas indicates an additional heating source
  - UV photons from the shock front and diffuse X-ray flux both insufficient
  - Electron conduction from the surrounding plasma
    - Balanced by evaporation from surface of knot

After Herschel

- Still want to study
  - Characteristics of pre- and post-shock gas
  - Interrelationship of molecular and neutral/ionic atomic gas
  - The role of heat condution by electrons
  - The possible role of molecular knots in protecting SN dust

SOFIA Cycle 2

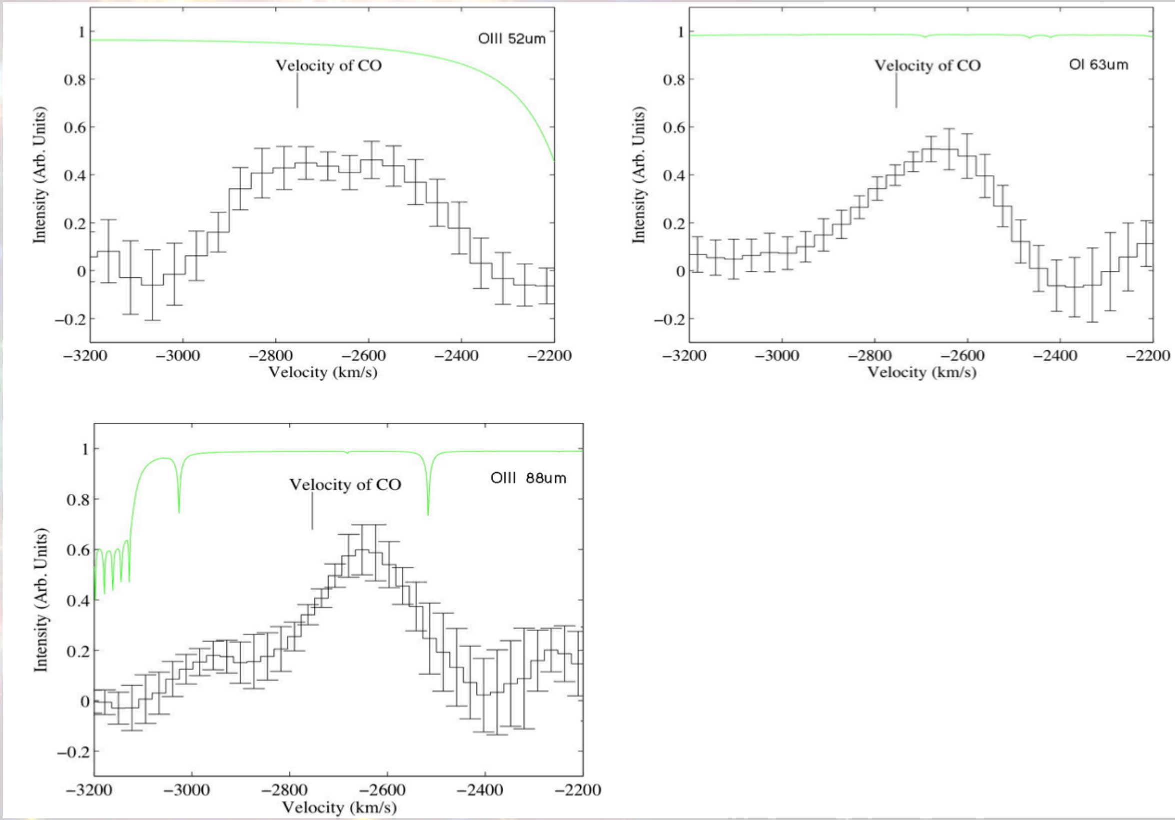
- Cycle 2 SOFIA observations with FIFI-LS
- Perfect for our broad lines (~400 km/s) and spatial variation
- I got to fly with SOFIA in April 2014!

SOFIA Cycle 2 observations

- [OIII] at 88 and 52 μm and [OI] 63 μm
  - [OIII] 88 μm detected with Herschel
  - Various critical densities to disentangle contribution from
    - lower density pre-shock photoionized zone
    - higher density post-shock photoionized zone
  - E.g. [OI] 63 μm has critical density of 10^5 cm^{-3}, tracing the dense post-shock gas and may be a main coolant of this gas

SOFIA cycle 2 observations

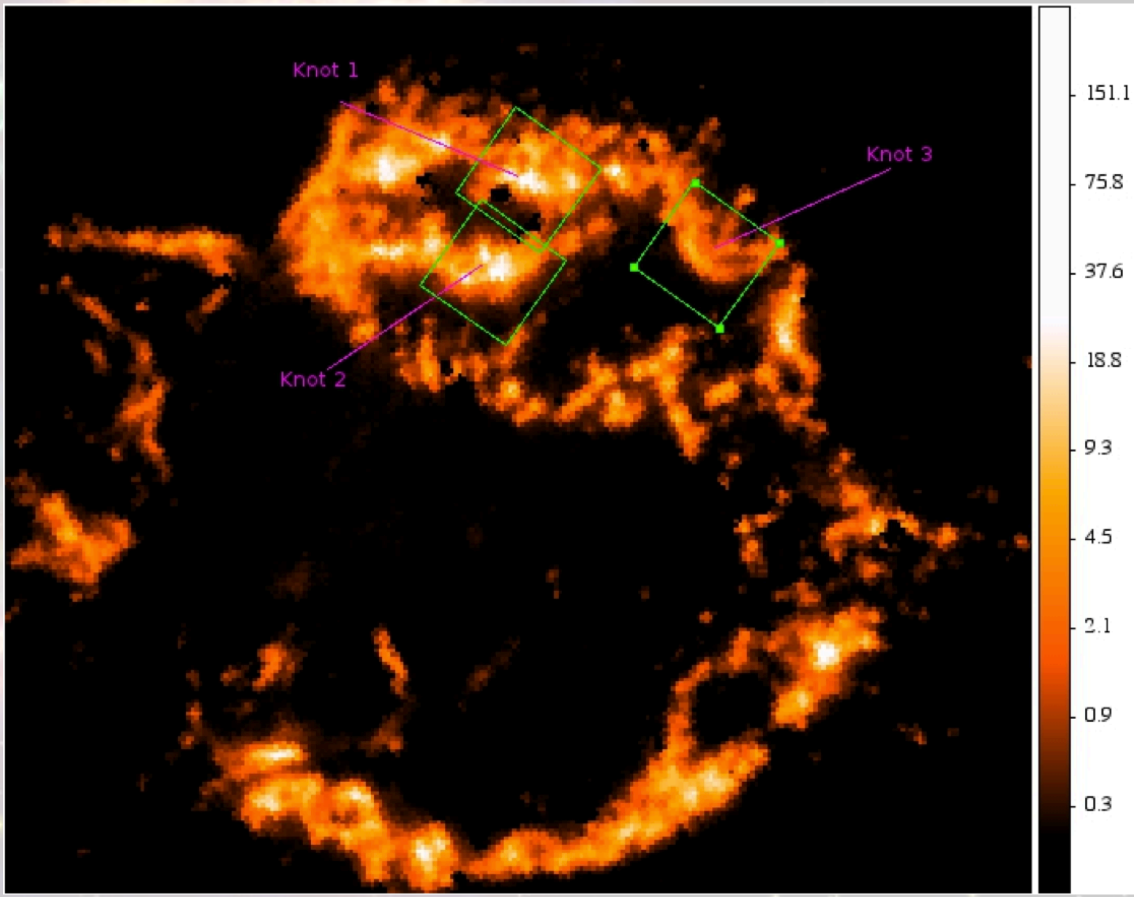
- Only preliminary results – but short integration times (~3min)
- Still needs to be corrected for atmospheric transmission and flux calibrated



Telluric absorption calculated by RATRAN shown in green

SOFIA Cycle 3

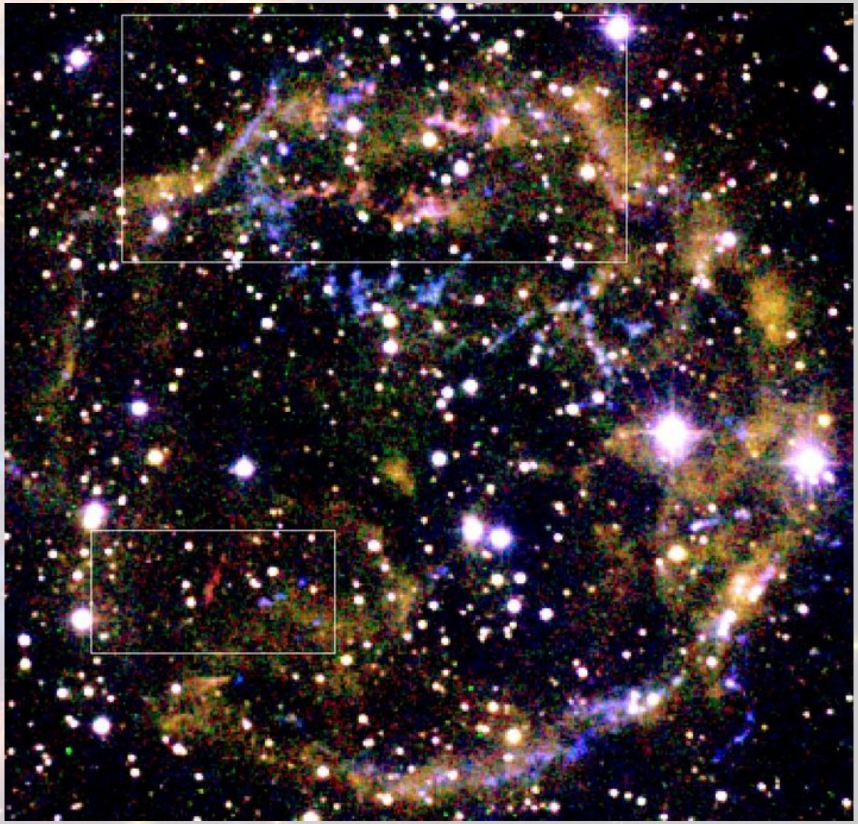
- Follow-up observations in Cycle 3
- Targeting the same lines at 3 CO positions in Cas A



4.5 µm Spitzer map of ro-vibrational CO emission in Cas A (Rho et al. 2009)

Summary

- Dense molecular knots in Cas A important for SNR impact and evolution
  - Study interplay with neutral/ionic gas
- Promising preliminary Cycle 2 SOFIA data; excited for Cycle 3 data!



Color image of Cas A, with CO 2-0 overtone emission at 2.3 µm in red, K-continuum in green and Pβ in blue (Rho et al. 2009)