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SOFIA Science Highlights

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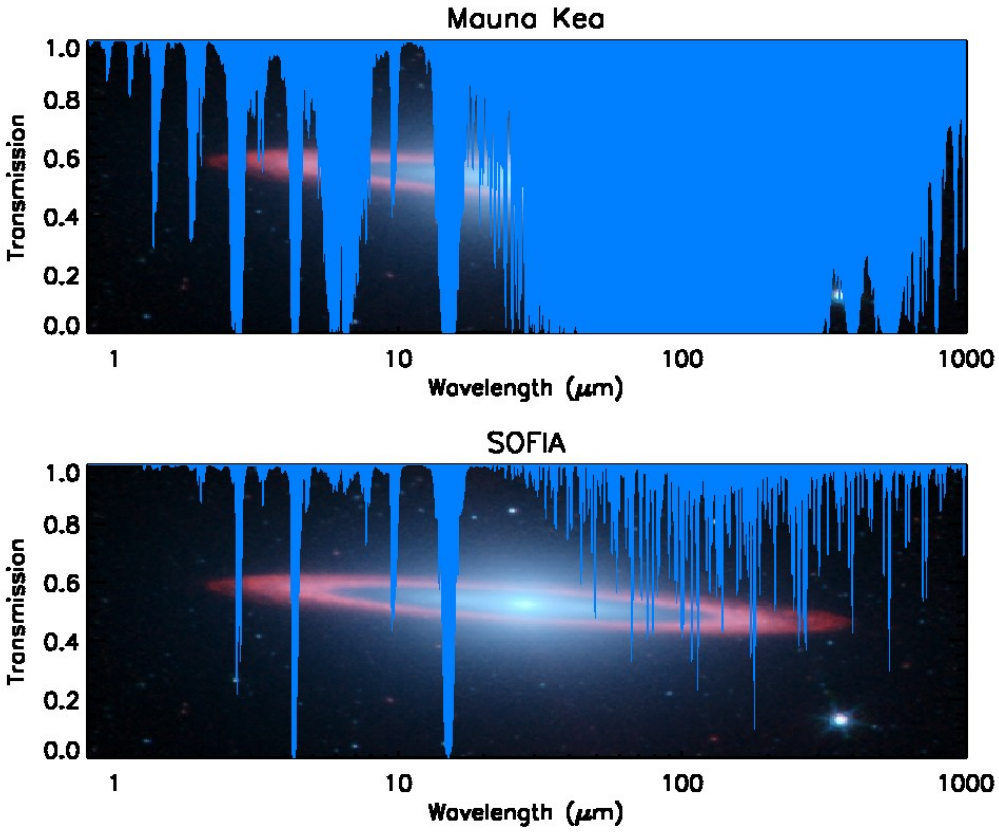
Outline of Material

- Why SOFIA
- Overview of 1st Gen Instruments
- SOFIA-FORCAST Imaging Observations of the Galactic Center and W3
- SOFIA-FORCAST Spectroscopy of Nova Del
- SOFIA-FLITECAM Spectroscopy of M82 Supernova 2014J
- GREAT Science
- Commissioning Science with EXES
- Special Experiments with SOFIA
- SOFIA Summary

Why SOFIA?

Why SOFIA?

- Infrared transmission in the Stratosphere very good: >80% from 1 to 1000 microns
- Instrumentation: wide complement, rapidly interchangeable, state-of-the art
- Mobility: anywhere, anytime
- Long lifetime
- Outstanding platform to train future Instrumentalists
- Near Space Observatory that comes home after every flight

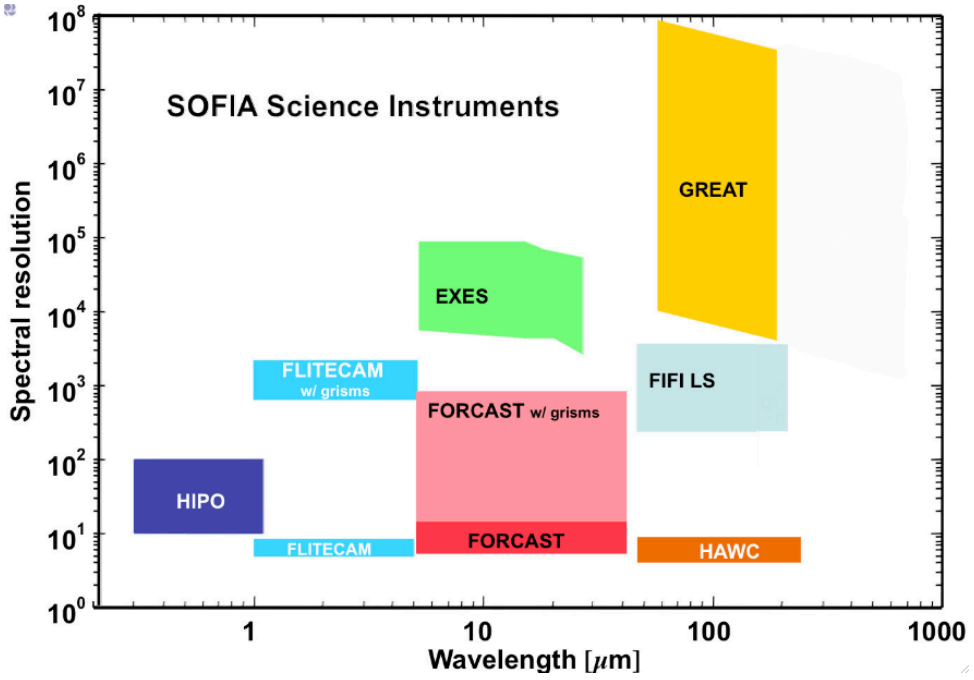


INSTRUMENTATION

SOFIA's Instrument Complement

As an airborne mission, SOFIA supports a unique, expandable instrument suite

- SOFIA covers the full IR range with imagers and low to high resolution spectrographs
- 6 instruments now in Operation
- SOFIA will take full advantage of improvements in instrument technology. There will be one new instrument or major upgrade each year.
- Will support both Facility Instruments and PI Class Instruments



SPECTACULAR FORCAST IMAGING and SPECTROSCOPIC SCIENCE

The Galactic Center Circumnuclear Ring

The Center of the Milky Way

- At the very core of our Galaxy, the Milky Way exists a very massive Black Hole with M~4x10^6 M_{sun}
  - Distance = 8 kpc
  - Evidence for massive object comes from orbiting stars seen at 1.6, 2.2 and 3.8 microns. Work done at the VLT (Genzel etal) and Keck Obs. (Ghez etal)

The Center of the Milky Way and SOFIA

- With SOFIA/FORCAST we studied the circumnucear dust at 19, 31 and 37 μm

  -- sharpest and deepest 37 micron image to date (~3 arcsec FWHM)

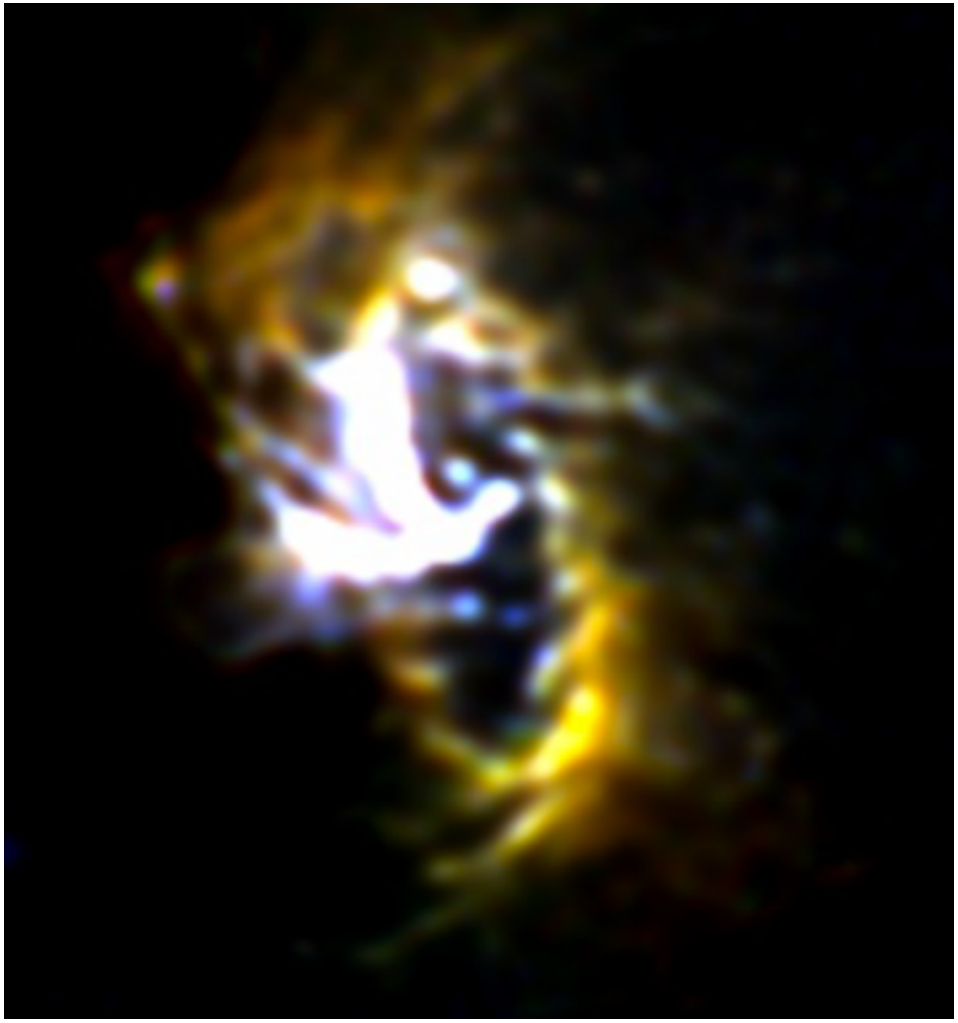
  --the central region around the Black Hole

  -- a region where massive stars might be forming

* Work done by Ryan Lau, Terry Herter, Joe Adams, Mark Morris and Eric Becklin. ApJ 2013, 775, 37.

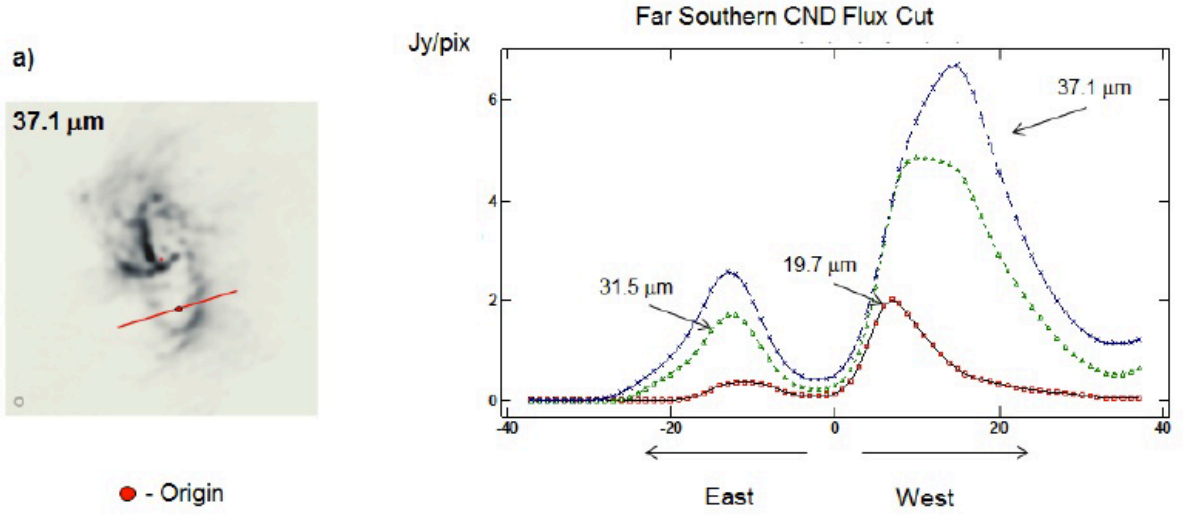
CNR at 19(blue), 31(green) and 37(red) microns

This is the highest resolution image of the Circumnuclear Ring ever obtained with ~3 arcsec FWHM



- White central emission is from the hot dust heated by ionized gas of the northern and eastern arms
- Almost perfect 1.5 pc radius ring is seen in cooler dust (T~100K) centered on the Massive Black Hole and tilted about 18 degrees to the line of sight and The Galaxy
- The ring is resolved with a width of about 0.3 pc
- There is interesting small structures along the ring, almost periodic in nature.

Line Cuts along the CNR in the South



- Line cuts across the center clearly show a color gradient from the inside of the ring moving outward
- This implies centrally heated, probably by young bright stars near the massive BH
- Western arm of the ring brighter than eastern arm
- No evidence for Star Formation

W-3 Star Formation Region Imaging

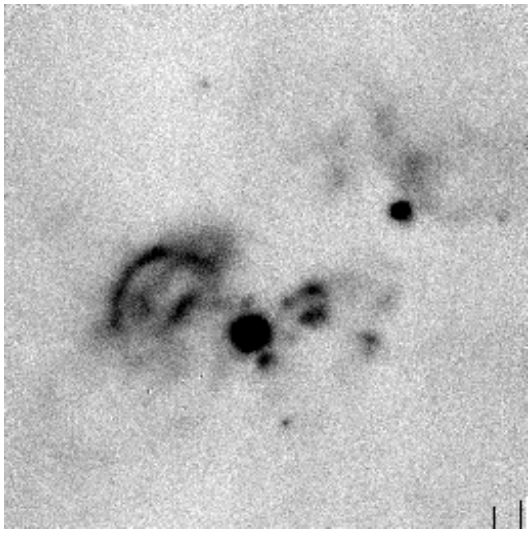
W3 Star Forming Region

- Star formation region in the Perseus arm at a distance of 2 kpc
- W3 has been identified with a cluster of intermediate and high mass young stars (Wynn-Williams etal 1972)

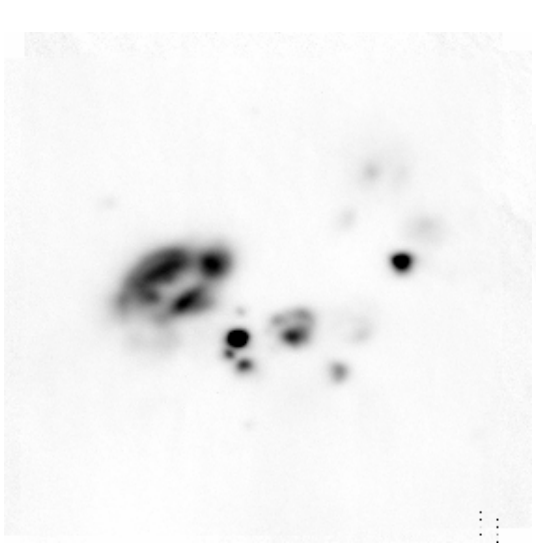
W3A Main

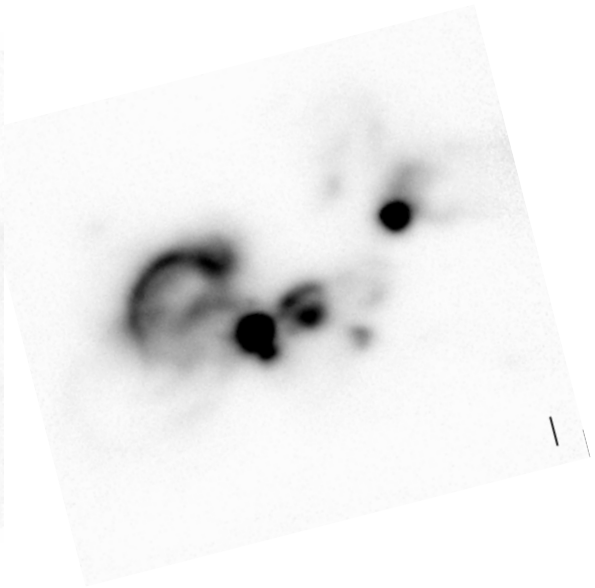
- The W3 Main region was a early science target of SOFIA with imaging at 6.4, 6.6, 7.7, 19.7, 24.2, 31.5 and 37.1 microns
- The extended HII region on the east side was the primary target. W3A data were published by Salgado etal 2012 ApJ Letters 749, L21.
- Other regions such as B,C,D and IRS 5, 6 & 7 have been observed but not published.

W3 Main



7.7 microns, PAH





37.1 microns

- Left: FORCAST image in 7.7 μm PAH feature
- Center: FORCAST 19.7 micron image
- Right: FORCAST image at 37.1 μm

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W3 Star Forming Region

- W3A on the left hand side of each image is an HII region with a almost symmetrical ionization front to the upper left seen in both the 7.7 micron PAH feature and the 37 micron continuum.

- The 19 micron peak emission Is inside the HII region between the ionization front and the exciting stars.

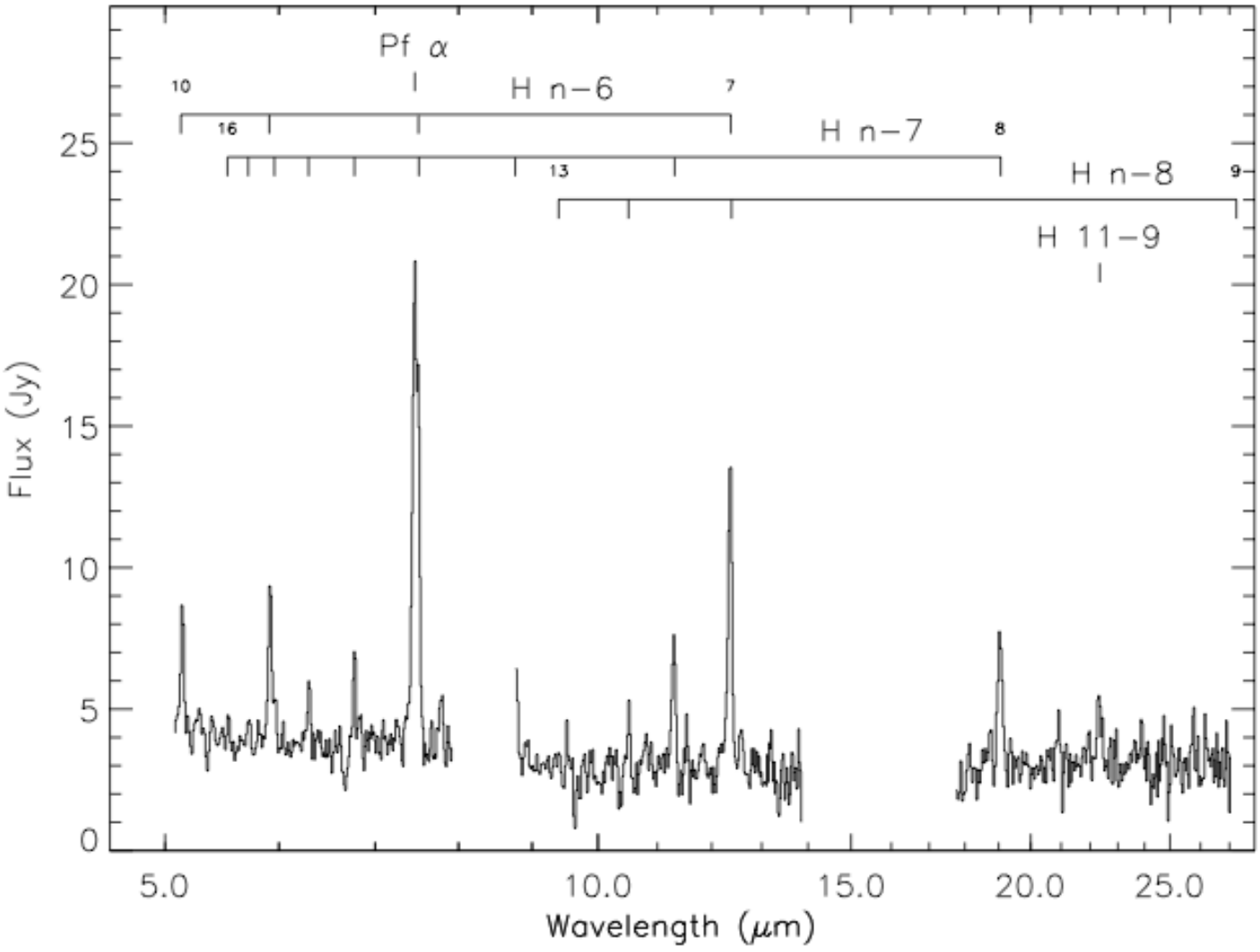
- Many questions: Why is the front so symmetric? Why are the PAH and 37 micron emission so well lined up? What is heating the PAH, the 37 micron emission, and the 19 micron emission? UV light from the exciting stars? Does Ly alpha heating play a role?

Spectroscopic Results with FORCAST
Nova Del 2013 Outburst

Nova Del Outburst of 2013 with FORCAST GRISMS

- Gehrz etal put in a proposal to observe recurrent Nova with the FORCAST GRISMs if an outburst occurred.
- On 13 Aug 2013 V339 Del was discovered to be in outburst.
- Erick Young activated the Target of Opportunity (ToO) FORCAST GRISM and Imaging observations.
- Goal was to look for strong IR metallic forbidden lines.
- Observations were taken on 10 Sept 2013, 24 days after maximum visible light.

Nova Del with FORCAST GRISMS

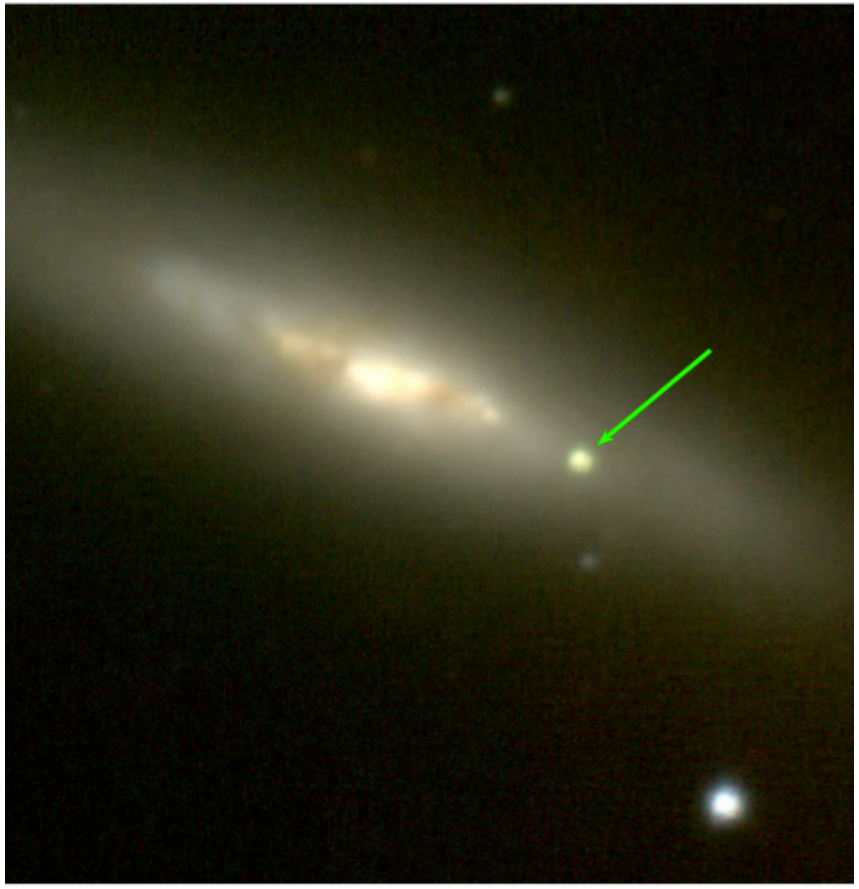


Nova Del

- Results reduced by Vacca and Helton show only ionized hydrogen emission.
- The density is too high (>E7 per cc) and the metal lines are quenched.
- Gehrz is surprised that [NeII] is not seen based on other novae.
- A draft paper is being worked on.

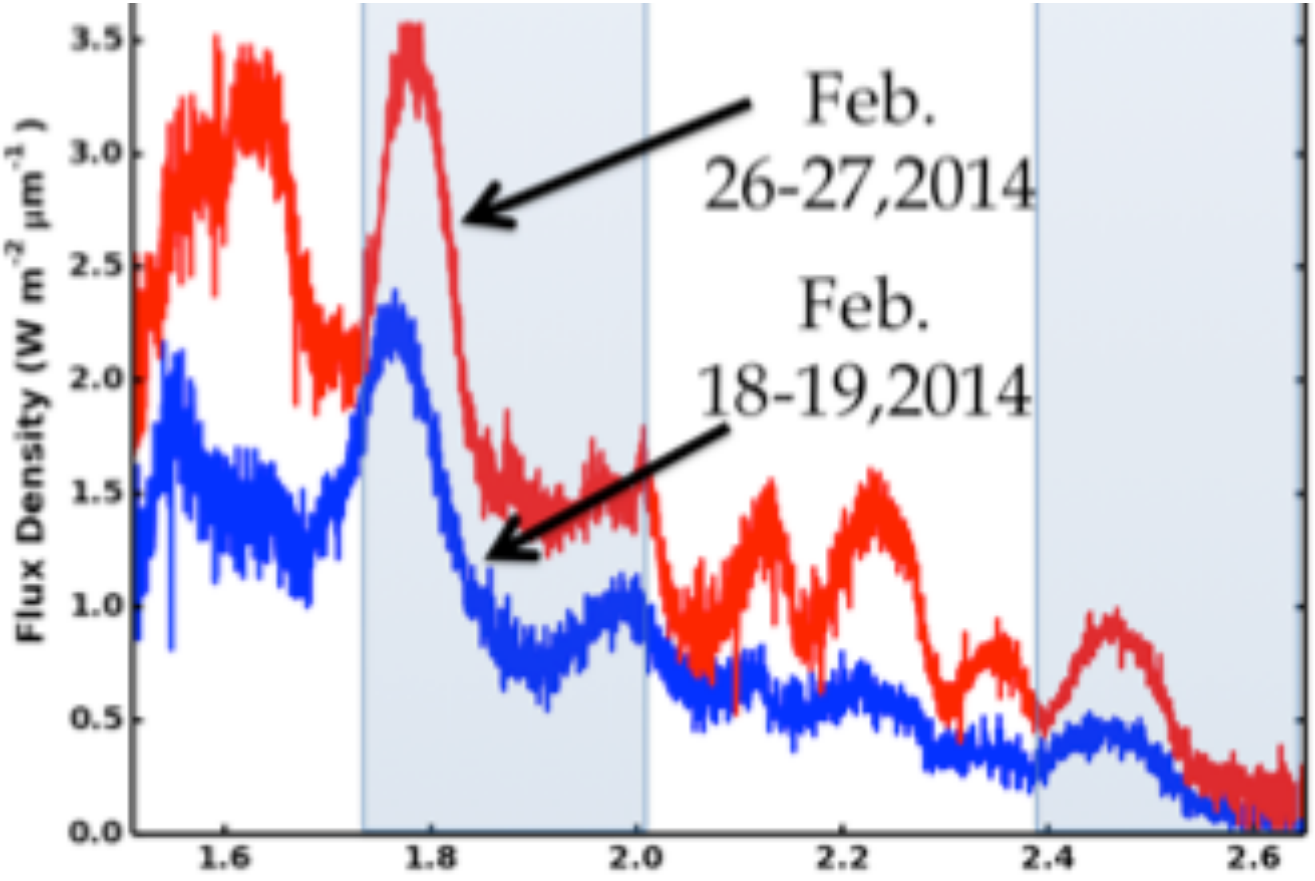
FLITECAM Spectroscopy of the Type Ia Supernova in M82 (SN 2014J)

FLITECAM SN2014J Data



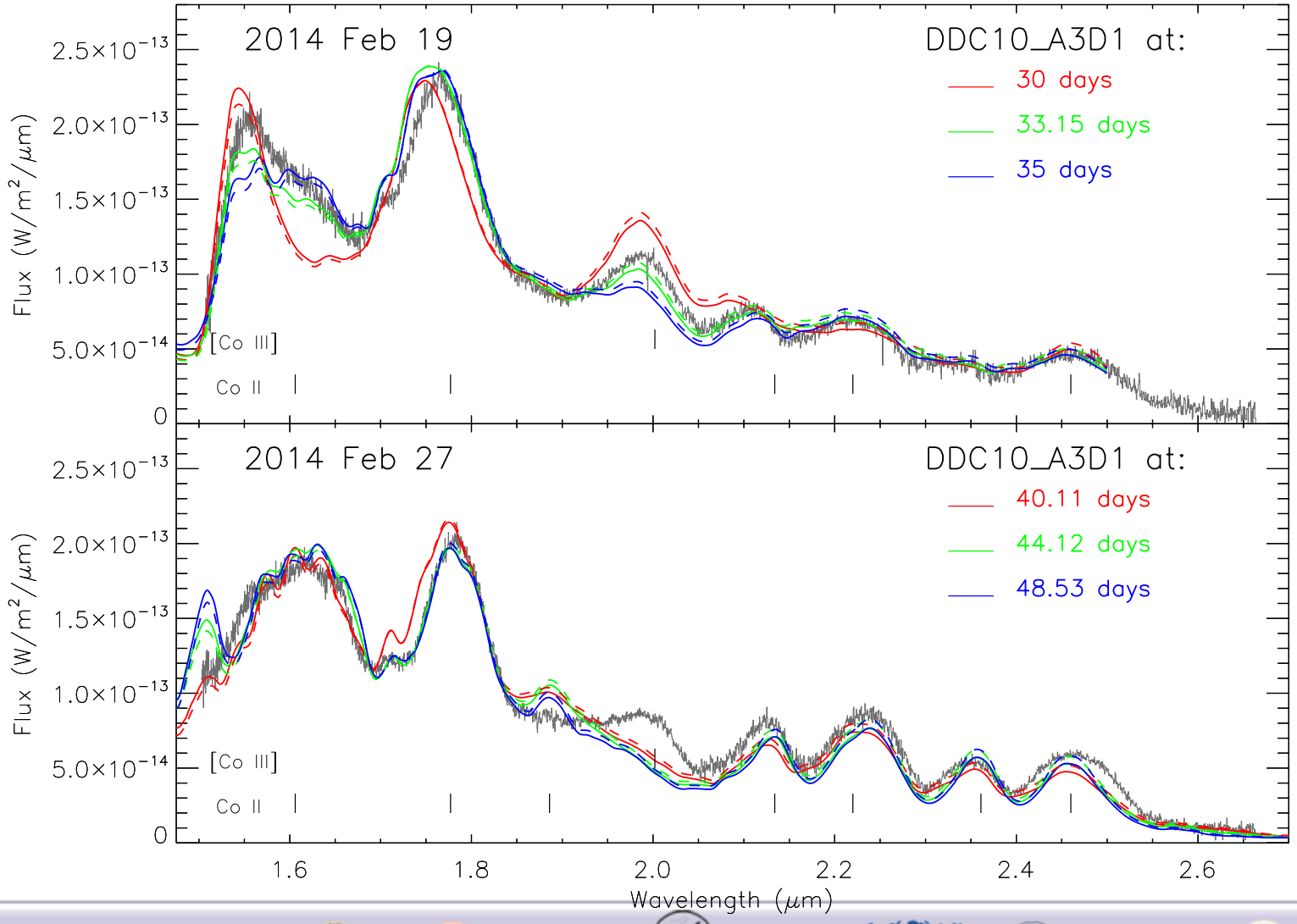
- Supernova Type Ia went off in Jan 2014
  - Started taking data at T+36 days
  - Spectroscopy + imaging
  - Activated accepted ToO proposal and Director's time for ToO proposals.
- Coverage: R~1200 spectra from 1 to 3.3 microns
- Results are published (Vacca etal 2015 ApJ 804)

FLITECAM and HIPO together (FLIPO): Supernova 2014J in M82 (Vacca etal 2015)



FLITECAM SN2014J Data

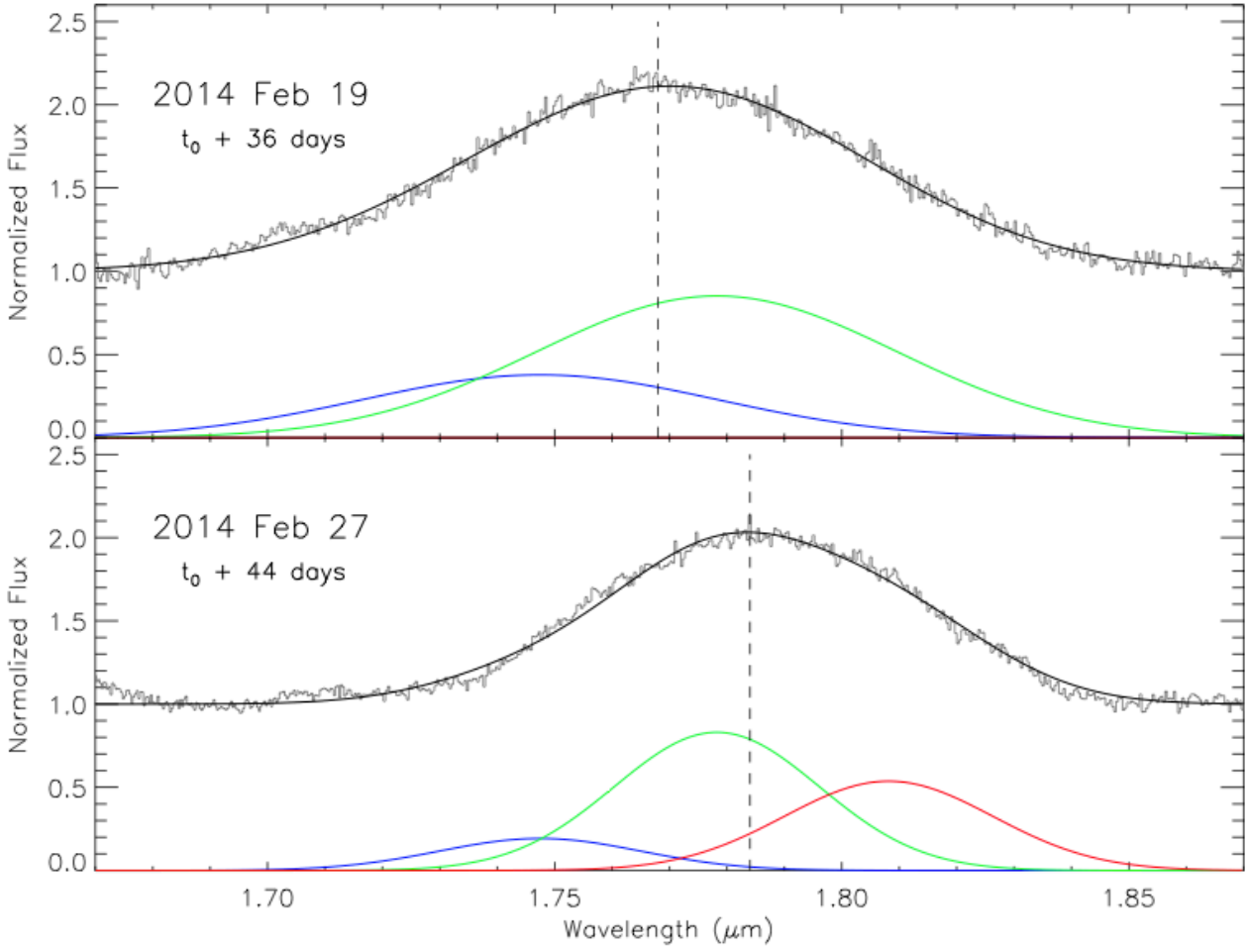
Vacca et al. 2015



SOFIA and SN 2014J in M82

- The strong line near 1.8 microns is identified as ionized Cobalt [Co II] (radioactive).
- Line width is ~10,000 km/sec.
- The models of Dessart etal show that the line is a blend of 3 lines.
- The wavelength shift seen in their models is due to the changes strengths of the 3 lines. The physics of the line changes is not discussed in the SOFIA paper.

Shift of the wavelength of the 1.77 micron emission line vs time.



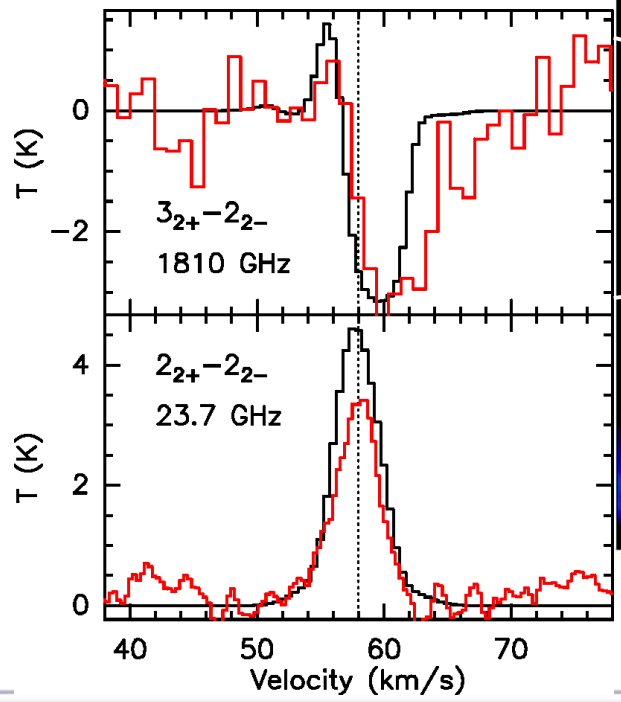
SOFIA and SN 2014J in M82

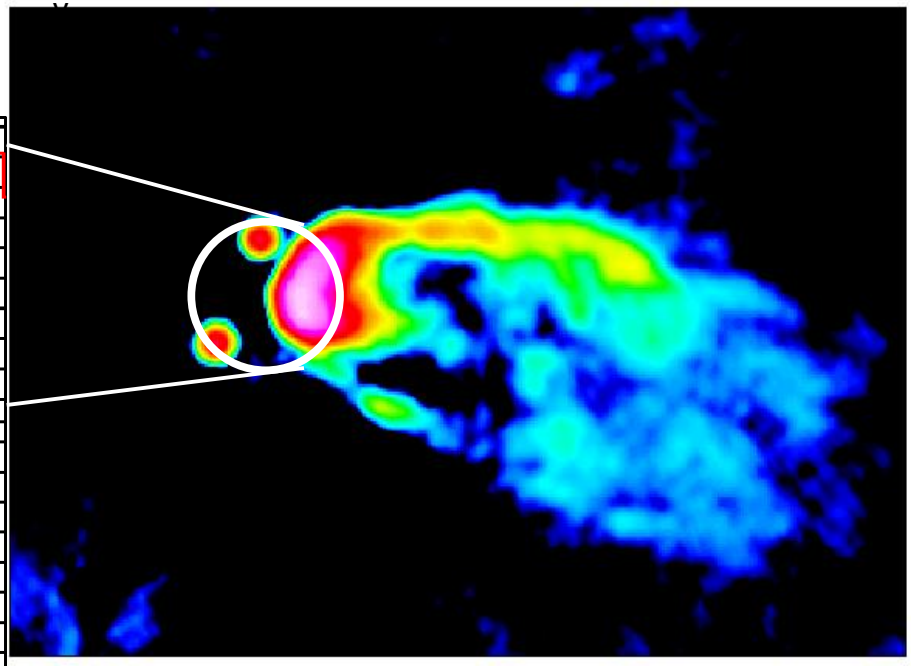
- **The most important result from my standpoint is that the models and the observations agree so well!!**
- **This 1.8 microns Cobalt seen 30 to 40 days after the explosion can be observed in future high z Type Ia SN with JWST/NIRSpec.**

GREAT SCIENCE

Science Results: probing infall

- Probing infall with ammonia absorption against dust continuum
  - -- case study: UCHIIR G34.3 → red-shifted absorption detected against the continuum at ~165 microns.
  - -- modeled with infalling protocluster envelope with a very high accretion rate ~E-3 Mo/yr Vsys





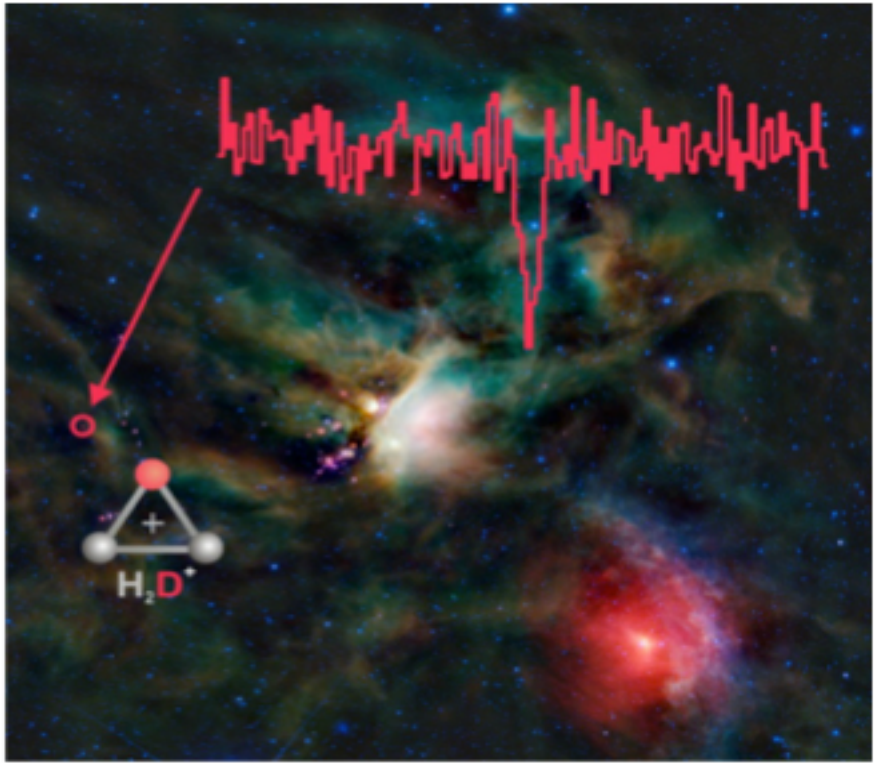
G34.26+0.15 VLA 3.6cm

In Fall of Material in Star Formation Regions

- Have now observed 8 regions in ammonia line, and 5 show infall with similar mass infall rates. Outflow is also seen in 3 regions.

- Results part of the special A&A issue to be published this year.

Para H2D+ in Rho Oph Dark Cloud with GREAT (IRAS 16293-24)



H2D+ in Rho Oph Dark Cloud (16293-24)

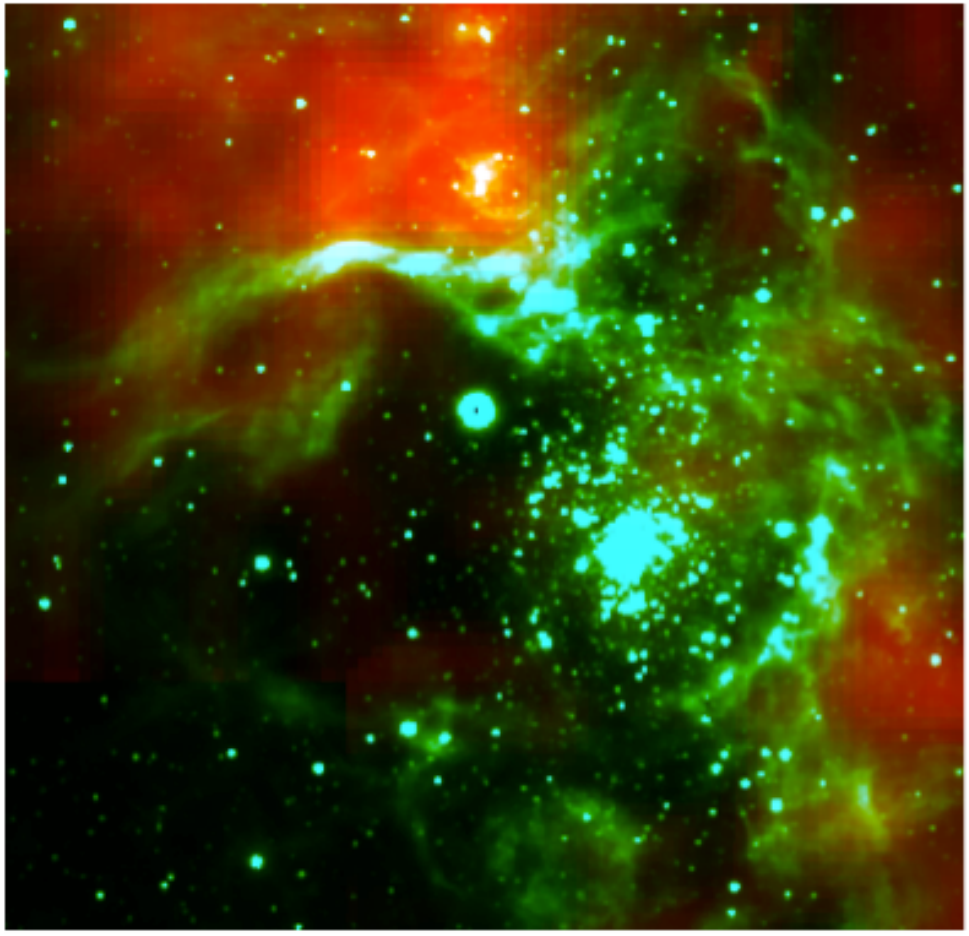
- Nature letter by Bruenken etal 2014 "H2D+ observations give an age of at least one million years for a cloud core forming Sun-like stars"

- GREAT observed Para H2D+ in absorption in a Rho Oph Dark Cloud core were many deuterium molecules are seen because it is dense (E6) and cold (T<20K).

- APEX observed Ortho H2D+ in emission (ground state is ~80 K)

- Explain how they get the long time scale for the cloud core.

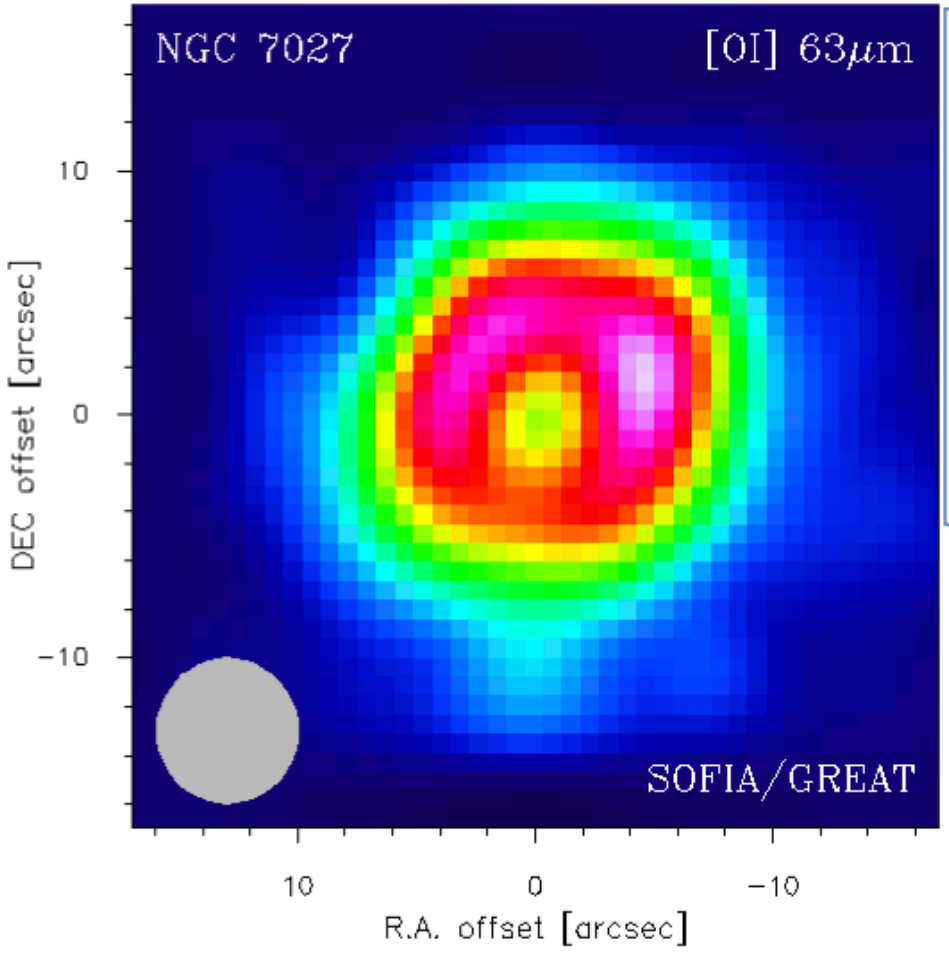
CII (red) in 30 Dor in LMC

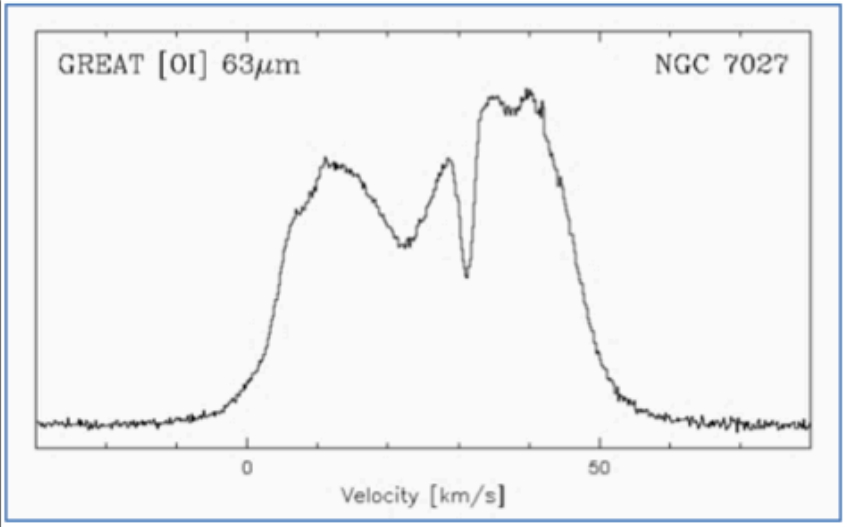


[CII] in Large and Small Magellanic Clouds

- [CII] is one of the primary cooling lines for the ISM
- The LMC and SMC have [CII] cooling, but under much lower carbon abundance than the Milky Way.
- [CII] traces dark molecular gas, not seen in CO (destroyed).
- Many observations from New Zealand.
- In principle, can be used to better understand how gas is cooled under early universe conditions.

GREAT 4.7 THz First Light





(Rolf Güsten & the GREAT Team)

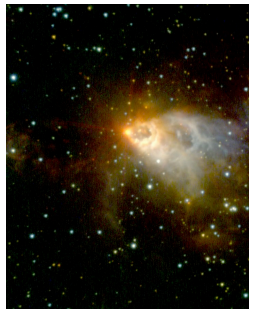
[OI] in the ISM

- [OI] is one of the primary cooling line of the Interstellar Gas in the ISM (along with [CII], but at 100x higher critical density)
- It is seen in many places to be very strong.
- In PDRs, in molecular clouds, in or near the ionized gas.
- GREAT's high spectral resolution R~E6 and spatial resolution of 6 arcsec will help sort out the astrophysics of [OI] emission and cooling of the ISM gas.

EXES Commissioning Science

R~100,000 Slit Spectrometer

Commissioning Science 1: Water Vapor in AFGL 2591



- ~10 M protostar in Cygnus region
- 0(0,0)→ 1(1,1) H_2O transition, and other H_2O lines
- Unobservable from ground
- T ~ 500 K, likely produced by evaporation of grain mantles
- Improves on R=2000 ISO studies
- Ap J Letters 802L 2015 Indriolo, N. etal
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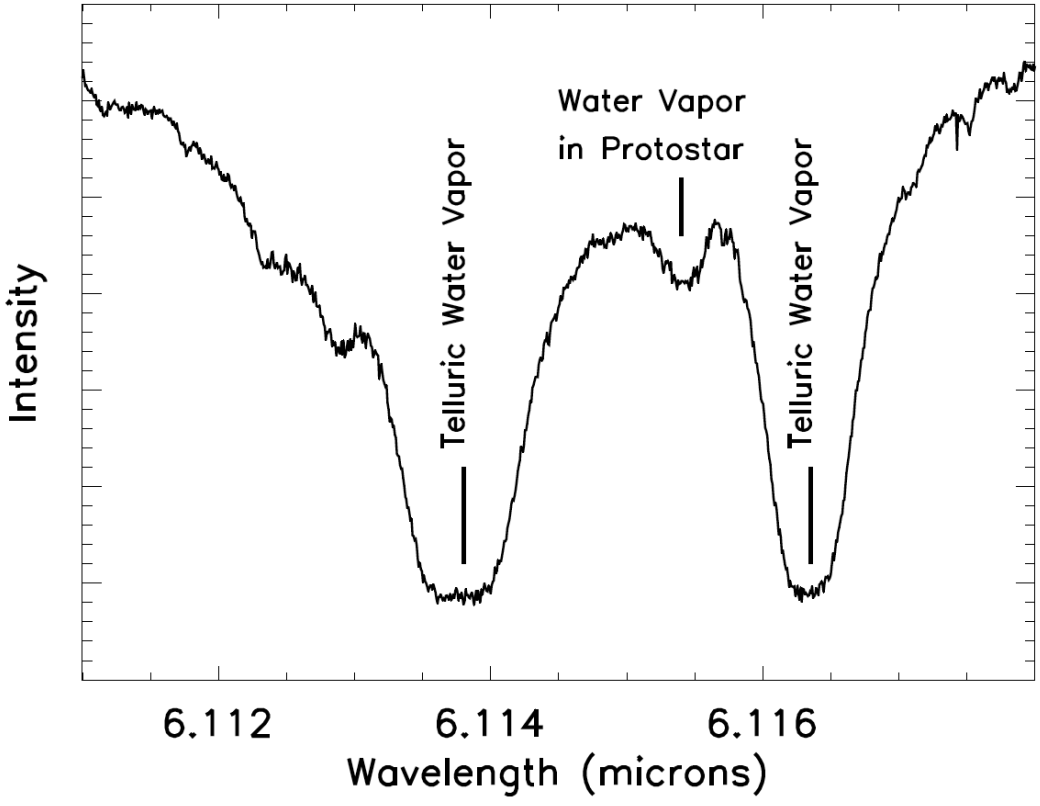
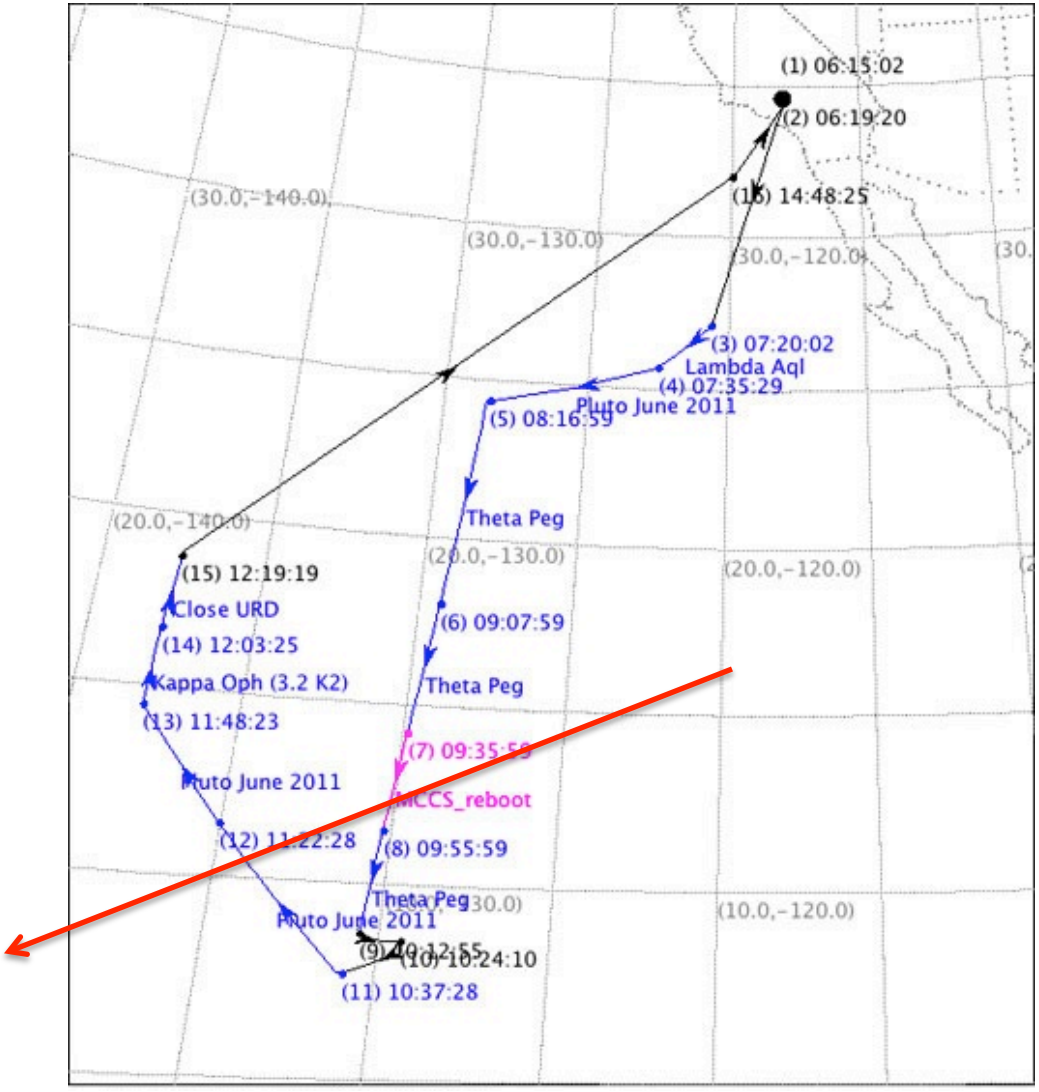


Special Experiments: Occultations, Transits and Eclipses

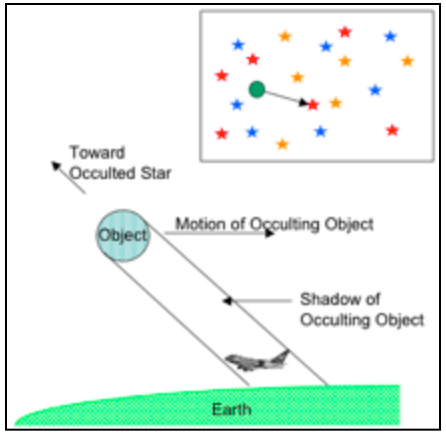
HIPO and FDC spots Pluto Eclipsing a Star



- Observed with HIPO in two channels and the FDC.

- Shadow travels at 85,000 kph (52,800 mph); SOFIA flew 2,900 km (1,800 miles) to capture the occultation

- **Hit center-line of occultation to within 100 km**



SOFIA Special Experiments

- Pluto Occultation of June 2011. Hit near the center line, Pluto atmosphere still there (shape of the light curve).
- Result published by Person etal. 2013.

- FliteCam, HIPO and FPC+ will observe the Pluto Occultation of June 29 2015, A 12th mag star occulted two weeks before the New Horizons fly-by from New Zealand.

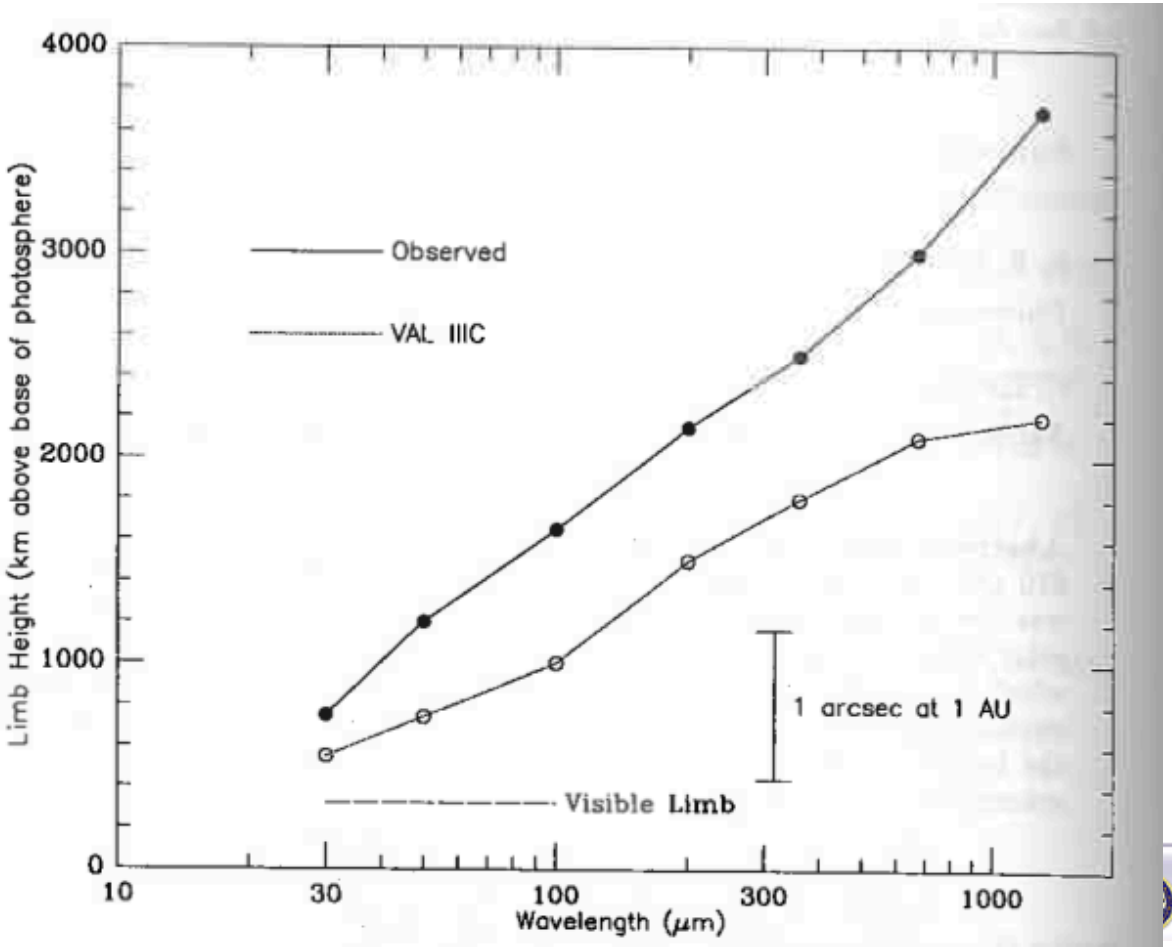
- Next total Solar Eclipse in North America will occur on Aug 21, 2017.

- Will SOFIA be able to observe a future eclipse to make unique measurements? I hope so!

Eric, Mike and Charlie on KAO for the 1988 Solar Eclipse

Figure C80. Eric Becklin (UCLA), Mike Werner (NASA Ames), Charlie Lindsey (University of Hawaii), 1988. Lindsey developed a full aperture sun filter for the KAO primary mirror. Here he's prepared to observe the solar eclipse before, during, and after totality.

KAO 1982, 1988 and Hawaii JCMT 1991 Eclipse Solar Limb Height verse Wavelength



Summary

- SOFIA with FORCAST, GREAT HIPO and 3 other instruments on SOFIA has produced outstanding science
  - >15 papers with FORCAST including spectacular Star Formation studies and Galactic Center results.
  - GREAT has many discoveries and 22 papers in a special edition A&A Letters. ~20 more papers to come from New Zealand deployment results. 63 micron [OI] line demonstrated…upGREAT
  - FLITECAM Spectrum of SN 2014J in M82 timely and unique
- SOFIA will be one of the primary facilities for far-IR and sub-millimeter astronomy for many years.