Using the mid- and far- infrared to measure the thermal structure of M supergiants winds – where it matters

Graham M Harper CASA, CU Boulder, USA

Co-Investigators
Matthew Richter - UC Davis: EXES PI and TEXES
Eamon O'Gorman – Dublin Institute for Advanced Studies, Ireland: Radio
Curtis DeWitt – UC Davis: EXES
Nils Ryde – Lund University, Sweden: Photospheric models
Edward Guinan – Villanova University, PA: long-term photometry
Tommy Greathouse – SWRI, TX: TEXES + EXES Instrument and Science Teams

Overview

- Motivation for study of mass loss
- Historical Overview Mid- Far-IR studies
- NASA-DLR SOFIA-EXES & NASA-TEXES
- What have we learned?
- Thoughts from the Wiggle-Room

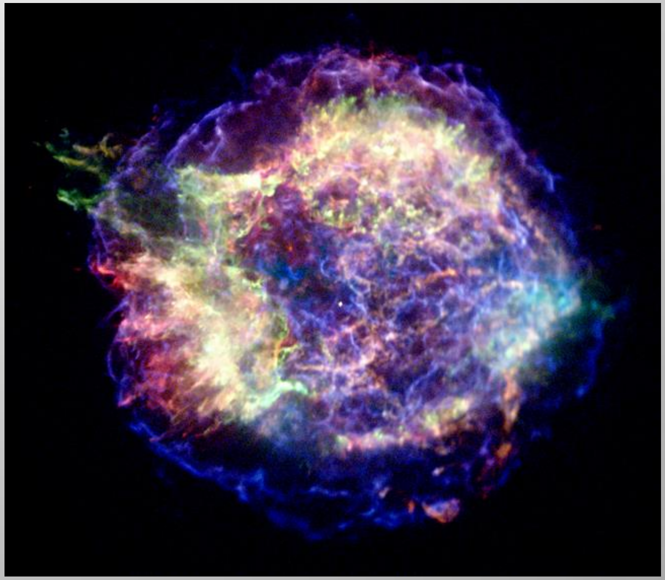
Using the mid-IR to measure the thermal structure of M supergiant winds – where it matters

Betelgeuse

NACO/VLT – 2009 near-Infrared
Credit: ESO and P. Kervella

10^5 yr ?

Type II core-collapse supernova



Cassiopeia A – Remnant (false color)

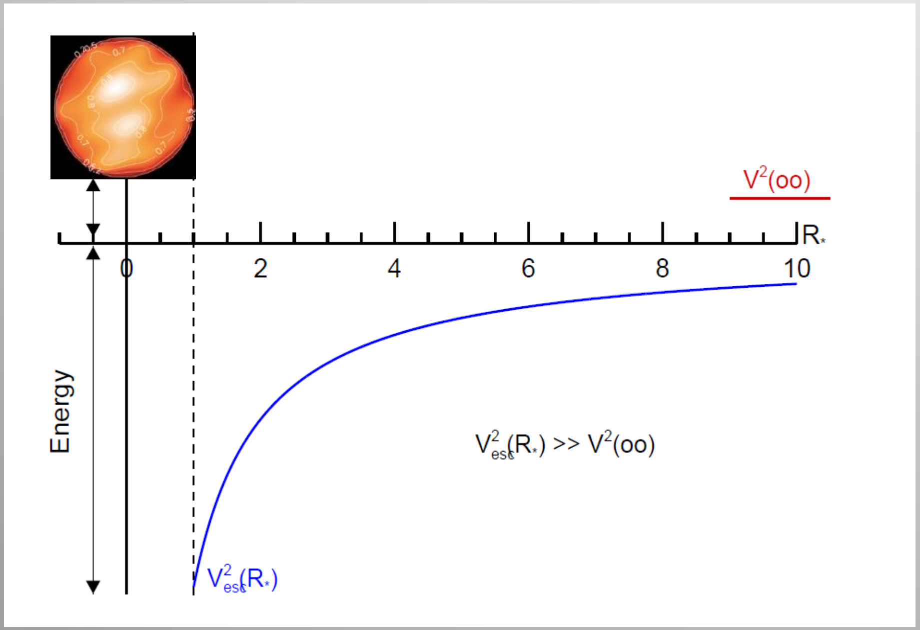
Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration. Acknowledgement: Robert A. Fesen (Dartmouth College, USA) and James Long (ESA/Hubble)

<u>Possible outflow drivers</u>

1) Radiation pressure on dust/molecules
2) Magnetic fields/ waves
3) Episodic ejections of mass
4) Pulsations and shock waves

Where is the best place to probe the outflow?

Where to look? Energetics!

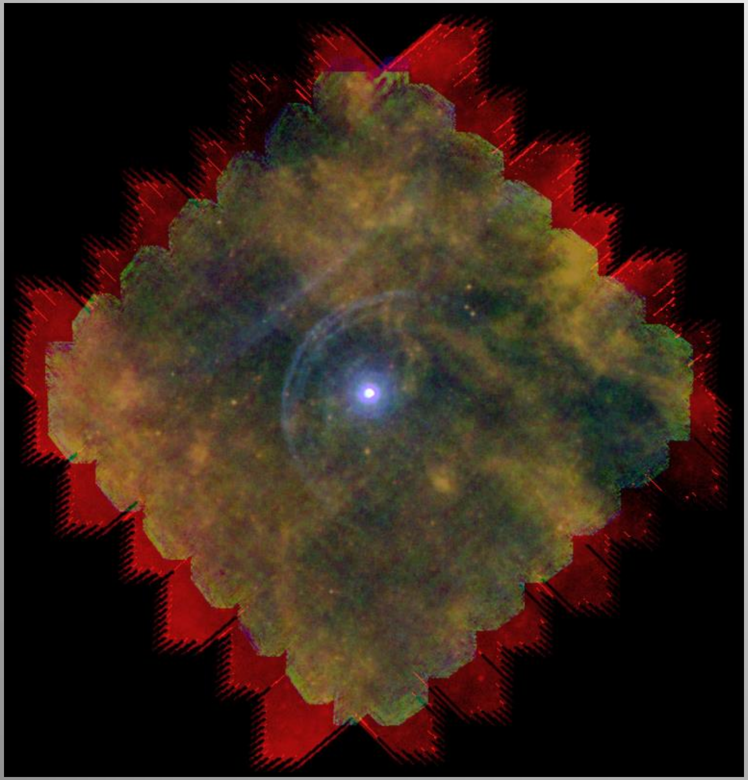


1) Most of the energy that goes into the stellar outflow is used to lift the mass out of the gravitational potential

2) KE of flow negligible fraction of energy budget < 5%

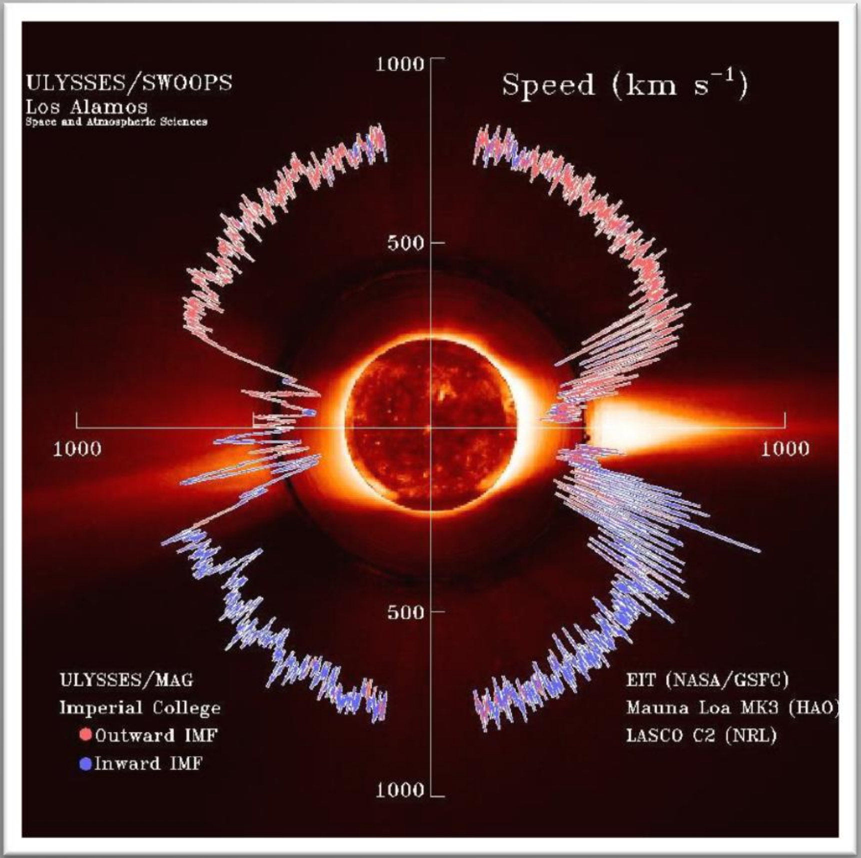
3) Probe the region close to star – where the signatures of mass loss most apparent

Vitals – Betelgeuse (≈Antares)



Spectral Type	Red Supergiant M2 Iab
Surface Temperature	3600 K (cool star)
Log(L/Lsol)	5.12
Distance	197 +/- 45 parsec (pc) 640 Light Years
Mass (Birth)	~20 M(sun)
Mass (Now)	~18 M(sun)
Mass Loss Rate	$3x10^{-6}$ M(sun)/yr (current)
Wind speed V_w	~10 kms^{-1} (current).~16 km s^{-1} (recent)
Age	~10 Myr
Time left?	~0.1 Myr (Nolan et al. 2015)
Origin	O-type (hot) main-sequence Runaway Star
Fate	Supernova Type II

Thermal Pressure (Parker-type)



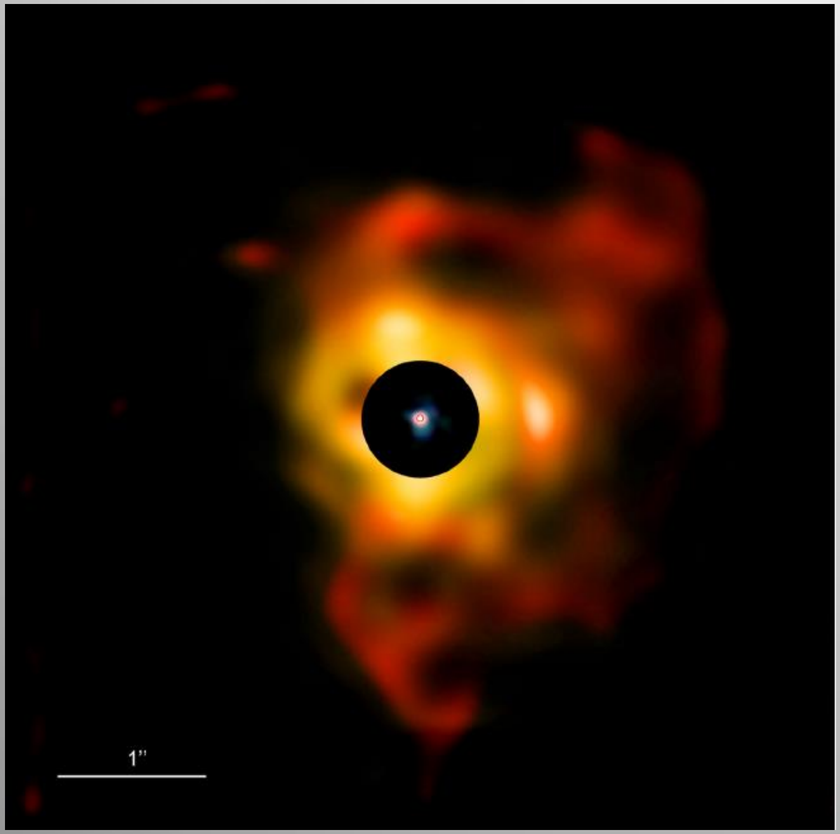
- T (solar) = 1-2 x 10^6 K
- T (α Ori) = 1-2 x 10^3 K

- V_{esc}/a (solar) = 620/150 ~ 4
- V_{esc}/a (α Ori) = 75/6 ~ 13

$$\dot{M}_{\rm tot} = 4\pi \rho_* a R_*^2 \left[\frac{v_{\rm esc}(R_*)}{2a}\right]^4 \exp\left[-\frac{v_{\rm esc}^2(R_*)}{2a^2} + \frac{3}{2}\right]$$

- Exponential wins
- Thermal Pressure don't work

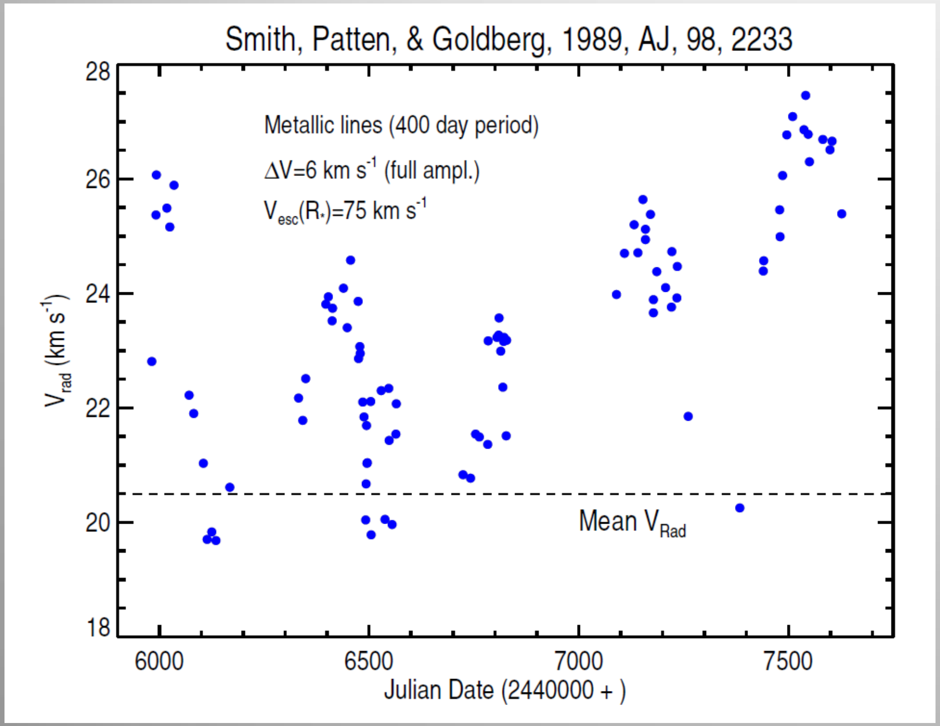
Radiation Pressure (IR+dust)



VLTI+VISIER Kervella et al. 2011 A&A 531, A117

- Dust images (VISIER) 6 filters
  - 7.76-19.50 µm
- Agree with earlier IR interferometry
- Consistent with Oxygen-rich dust, silicates, alumina
- Bright (incomplete ring)
  - Radius ~0.9 arcsec
- **Most dust observed at 30R***
  - **No working models**

Radial Pulsations?



- Early M Supergiants
  - Semi-regular variables
- ΔV = 6 km s^{-1} (peak-to-peak)
- $V_{esc}(R_*)$ = 75 kms^{-1}
- What is velocity of C-O-M?

- Cf Mira variables
- ΔV= 25 kms^{-1} (peak-to-peak)
- $V_{esc}(R_*)$ = 50 kms^{-1}

- Arroyo-Torres, B. et al. 2015
  - A&A, 575, p. 50
- **Radial pulsation models don't work**

Were it not for magnetic fields, the Sun would be as uninteresting as most astronomers seem to think it is..“ - R.B Leighton, 1969

Betelgeuse CSE Observational Timeline (Space Era)

1984 HA
Alfven-wave
model

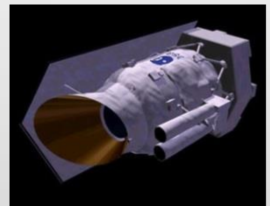
1986 GH
CSE Ionization
model

1991 RG
Thermal CSE
model

1992 KAO

1993 CSO

1996 ISO



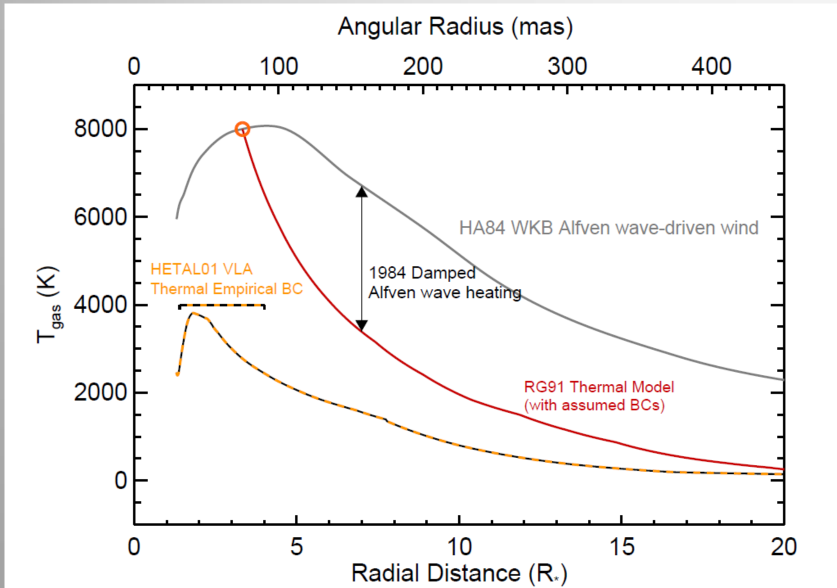
1997 VLA

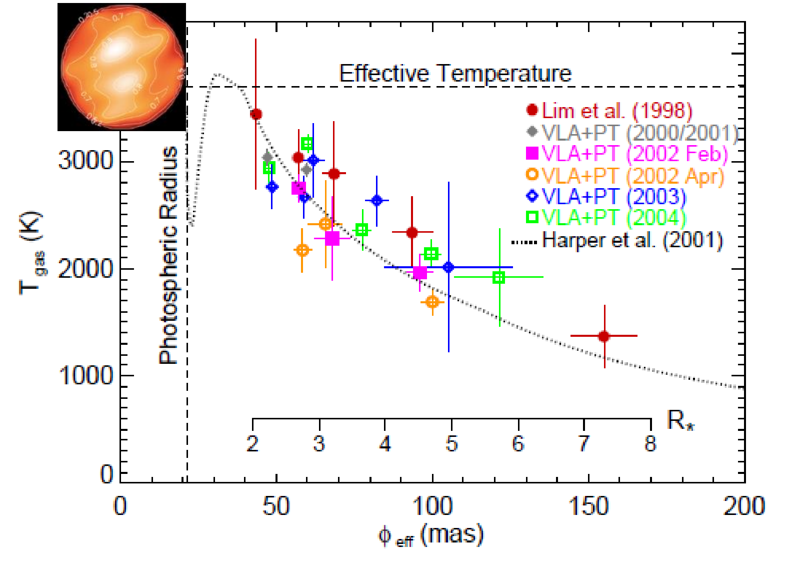
2005 IRTF

2010 Herschel

2015 EXES

Some Background: Shake-up of 1998

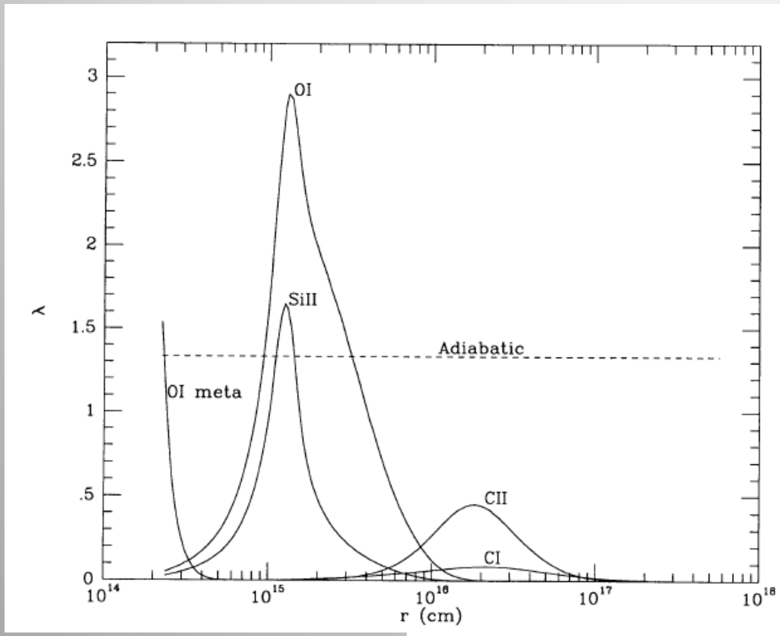


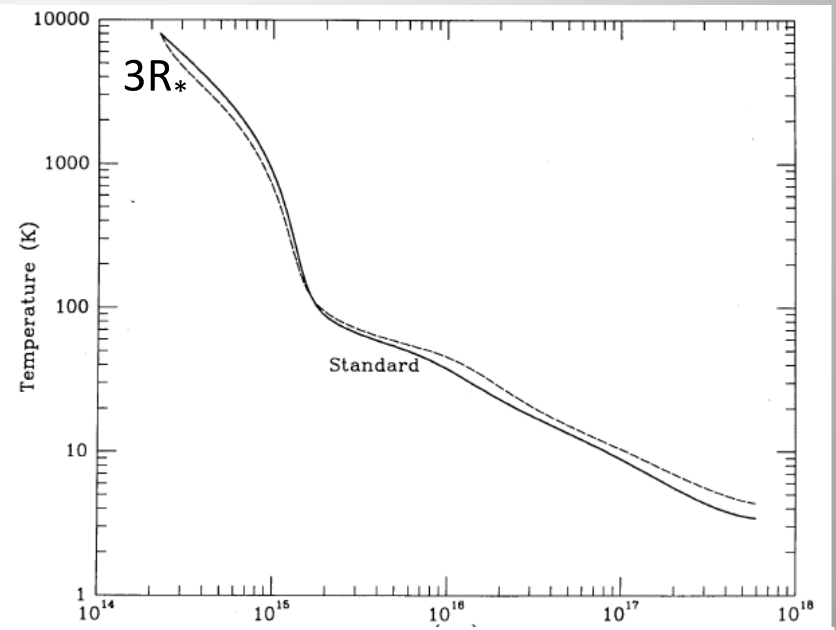


- Prior to 1998 - consensus that outflow was **T~8000 K** and magnetically driven
  - Theoretical model (HA84)
  - Spatially unresolved radio observations
  - Ultraviolet images and spectra from Hubble Space Telescope (+*IUE*)

- In 1996 spatially resolved cm-radio maps from the VLA showed the “average” temperature is **T~1500-3500 K** – much cooler than expected
  - Lim et al. 1998 Nature, 392, 575
  - O’Gorman et al 2015, A&A, 580, A101
  - No velocity information from radio

Rodgers & Glassgold 1991- CSE Thermal Model





- Semi-theoretic model
  - 1991 ApJ 382, 606
- Balance between line and adiabatic cooling and dust-drag heating

The radial temperature structure can be compactly described by

$$\frac{d\ln T}{d\ln r} = -\frac{4}{3}\left(1+\frac{1}{2}\frac{d\ln v}{d\ln r}\right) + \sum_i \mathcal{H} - \sum_j \mathcal{C} \quad \lambda = H,\ C$$

(Goldreich & Scoville 1976 ApJ 205, 114) where $\mathcal{H}$ and $\mathcal{L}$ are the heating and cooling rates for different processes, i and j, per unit mass, multiplied by the local dynamical time-scale (r/v) and divided by the thermal energy.

11

Ground term fine-structure cooling lines

Transition upper-lower	Wavelength (µm)	Texc (K)
[O I] 1 – 0	145	98
[O I] 2 – 1	63	228
[C II] 1/2 - 3/2	157	91
[C I] 1 – 0	610	24
[Si II] 1/2 – 3/2	34.8	413
[S I] 1 - 0	56.6	254
[S I] 2 - 1	25.2	571
[Fe II] 7/2 – 9/2	25.99	550
[Fe II] 5/2 – 7/2	35.3	960

Notes:
Oxygen-rich atmospheres
Low FIP elements photoionized by stellar UV field
Molecules 10x under abundant in CSE (not fully associated)

Haas & Glassgold 1995

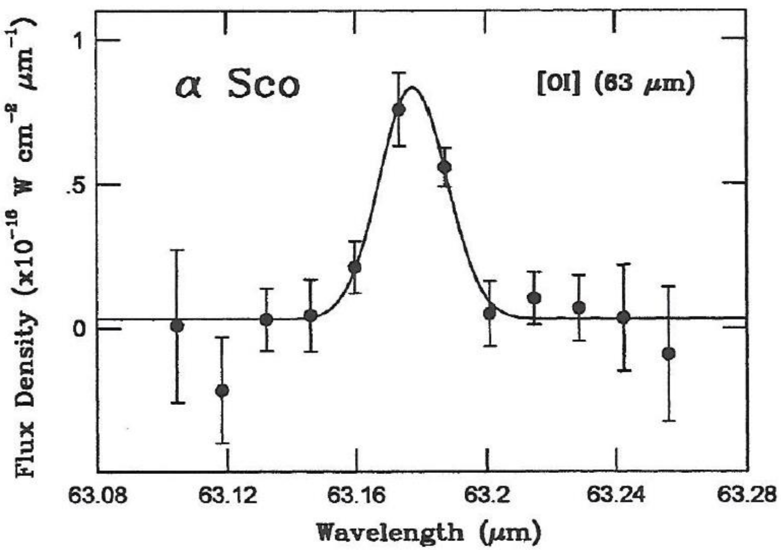


Figure 2. The [O I] 63 μm line in α Sco on 93 May 23.

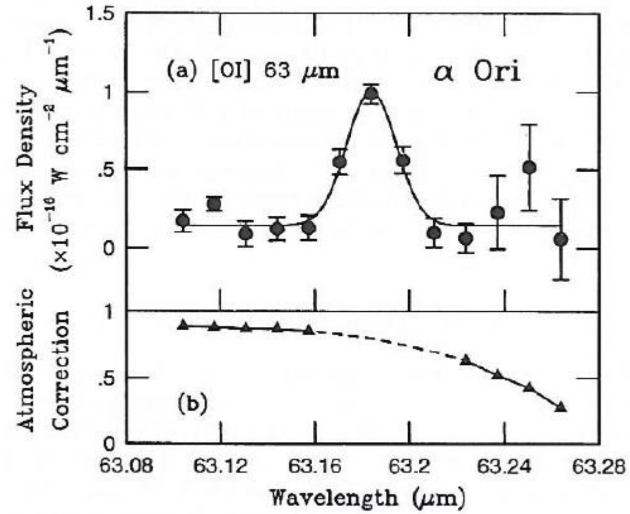


FIG. 1.—(*a*) The [O I] 63 μm spectrum of α Ori with a superposed least-squares fit. (*b*) The atmospheric correction determined by ratioing 63.2 and 62.7 μm spectra of the Kleinmann-Low nebula. The dashed region is an interpolation across the strong [O I] line present in KL.

- Kuiper Airborne Observatory
- 0.91 m
- Cryogenic Grating Spectrometer (CGS)
- R~3,000 Erickson et al. 1995

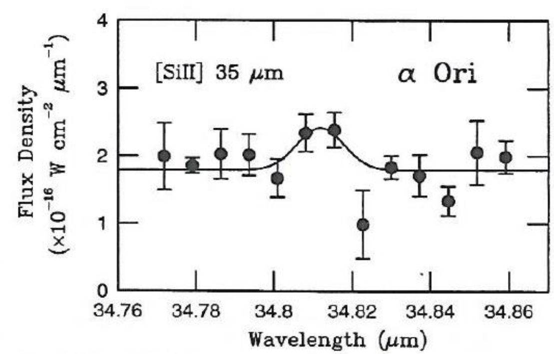
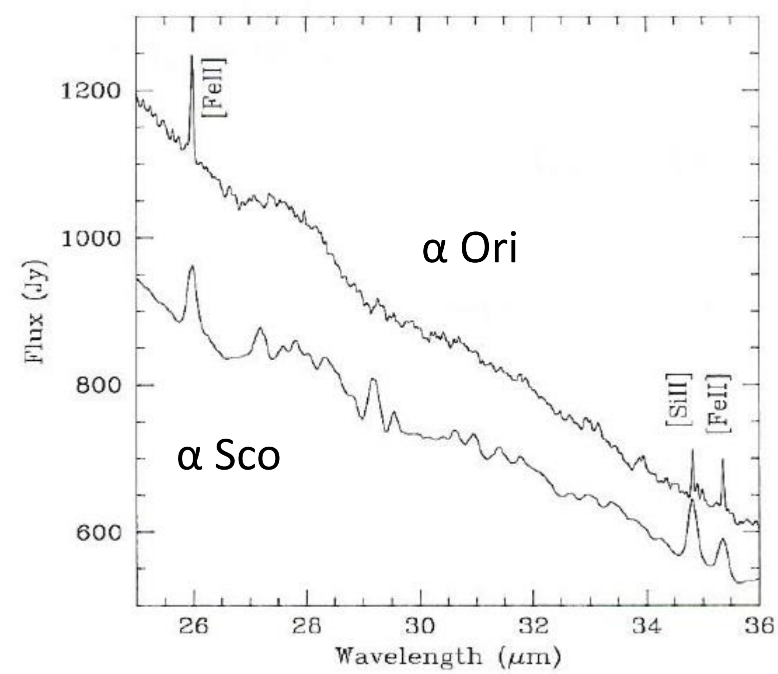
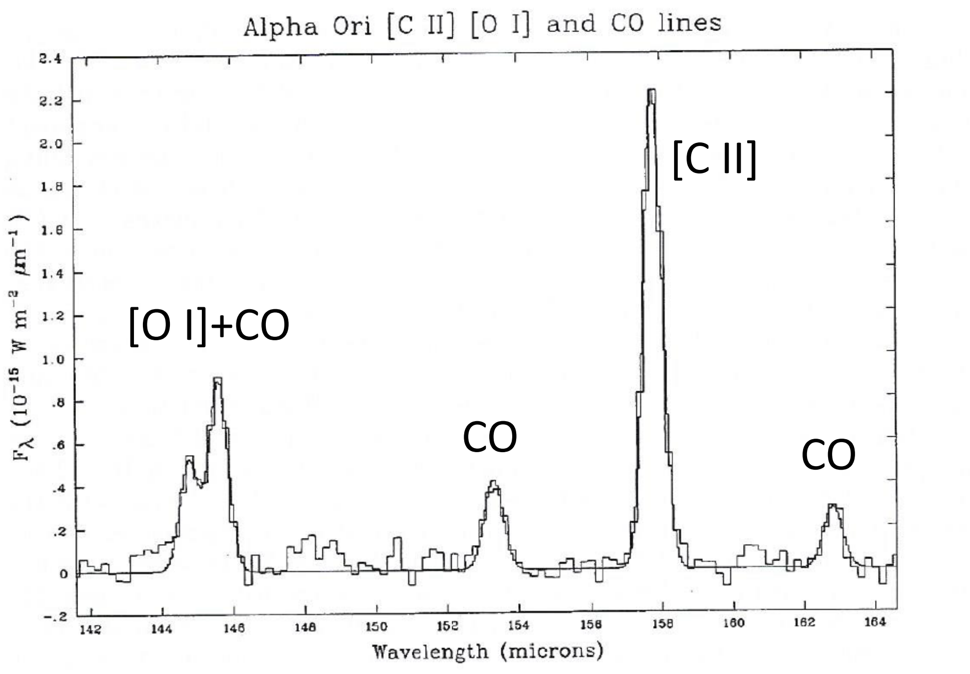


FIG. 2.—The [Si II] 35 μm spectrum of α Ori with a superposed least-squares fit.

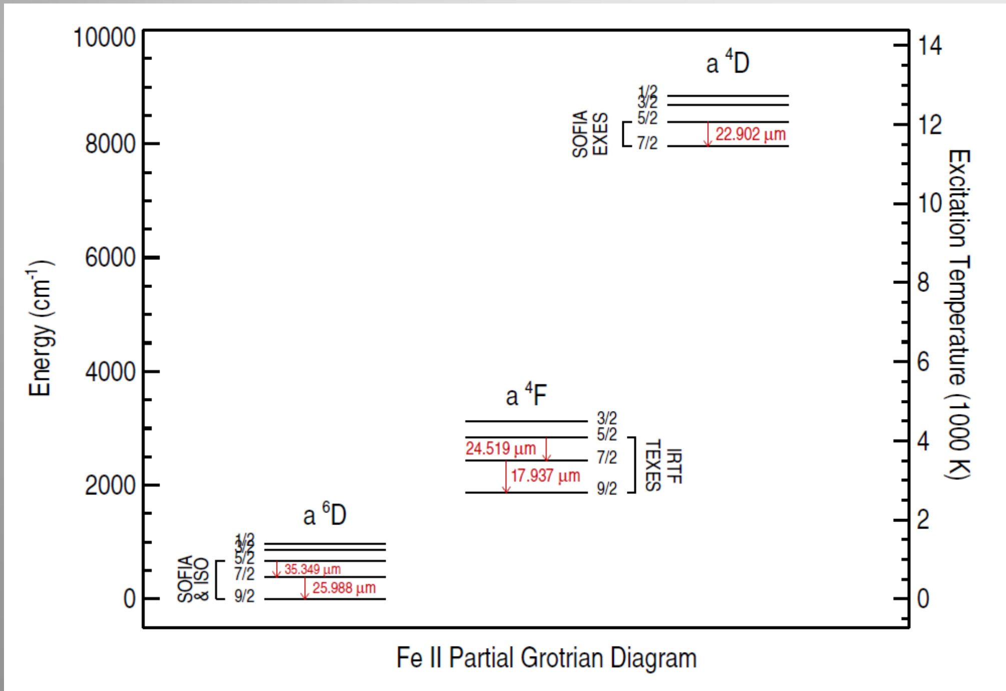
Infrared Space Observatory





- Left: Justtanont et al. 1999 A&A 345, 605
  - SWS Grating R=250, 1000
  - Strong [Fe II] emission
- Right: Barlow 1999 - 2 days before end of ISO mission
  - Background and continuum subtracted
  - CO significant emission (is it a coolant?)

Using Fe II (Fe^+) as a Temperature Probe



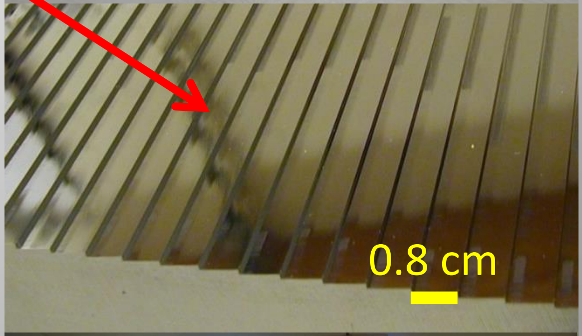
1) Constrain temperature using iron atoms with one electron stripped off: Fe II
2) Dominant ionization state
3) Multiple transitions from same ion
   1) $A_{ji} = 10^{-2}\ s^{-1}$
   2) $C_{ji} = nH \times 10^{-9}\ s^{-1}\ cm^{+3}$
   3) $nH > 10^{9}\ cm^{-3}$

   Metastable levels (Boltzmann Dist.)
4) Use EXES to dial-up which transitions to observe
   1) 22.902 µm (T_{exc}=11,700 K)
   2) 25.988 µm (T_{exc}= 540 K)
5) Use TEXES
   1) 17.937 µm (T_{exc}=3,400 K)

SOFIA-EXES as a thermometer

- Echelon-Cross-Echelle Spectrograph (EXES)
  - PI-class Instrument Matt Richter, UC Davis
  - Compact design based on Michelson 1898 Echelon – small enough to fit on SOFIA
  - high spectral resolution - 6 kms^{-1}
  - Wavelength range: 4.5 – 28.3 µm

- Cycle 2 Project: Dial-up selected spectral features sensitive to different temperatures
  - Optimum features are in mid-infrared (water vapor clobbers the stellar signal)
  - Use SOFIA flying at 12.8 km (42,000 ft)
  - Use Doppler effect to measure flow velocities and locate where in outflow you the temperature is measured



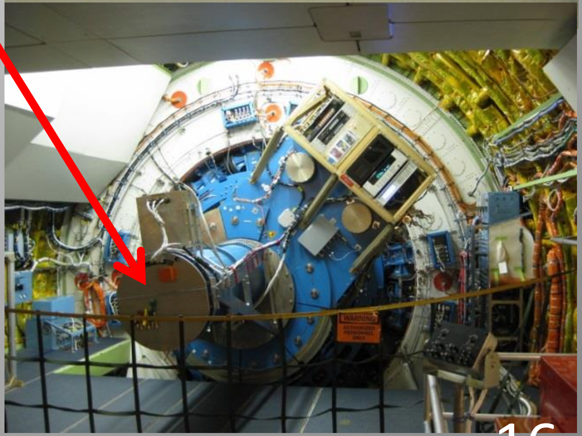
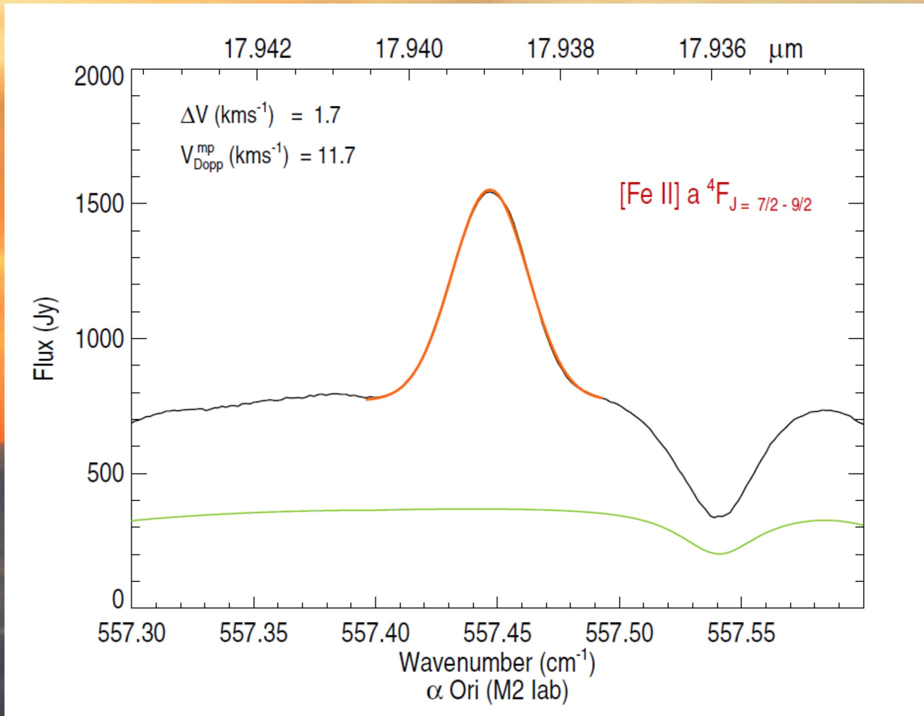
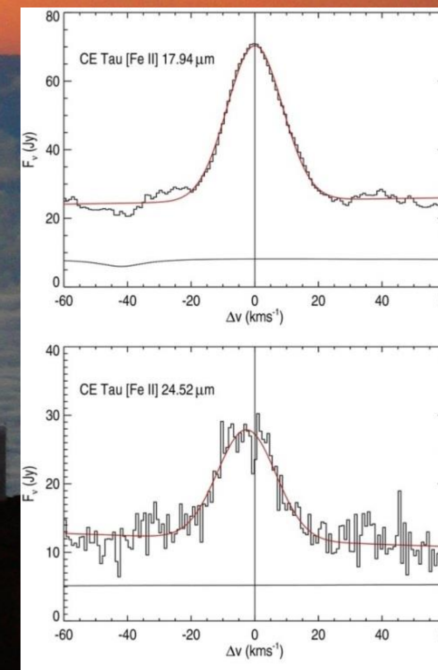


Image Credit: Taylor S. Chonis © 2015

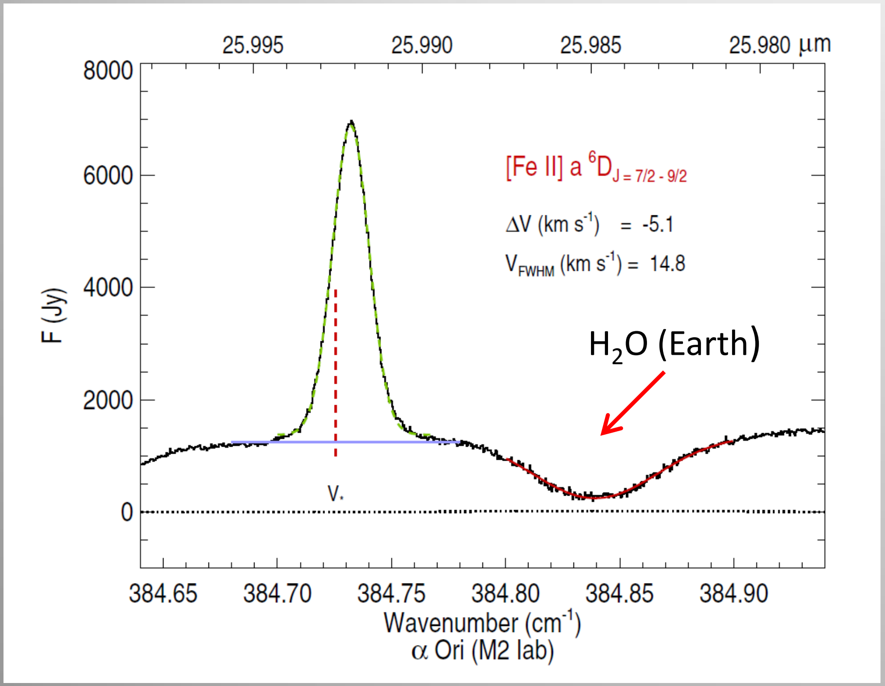




NASA IRTF with TEXES (PI J Lacy)

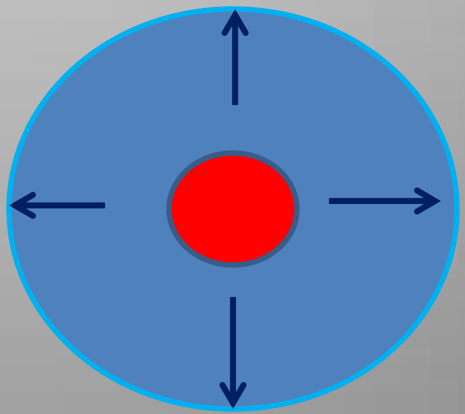
Profiles: close to Gaussian (near rest): formed in low velocity, turbulent gas – similar properties in small M supergiant sample:

SOFIA-EXES [Fe II] 25.99 µm emission

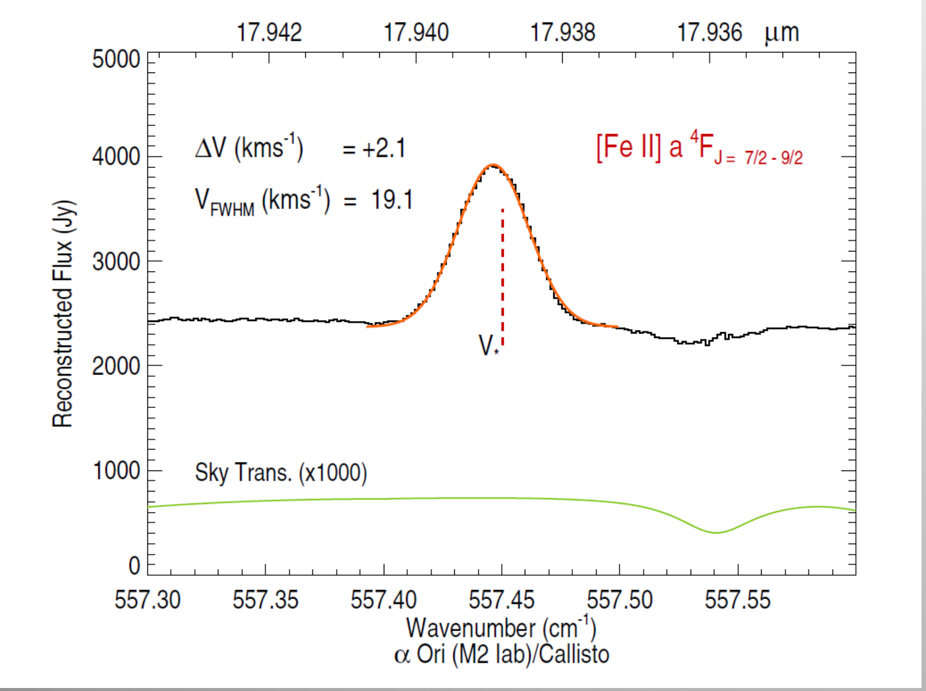


- T_{exc}=540 K
  - Flux consistent with ISO SWS spectra
  - **Key result ~5 kms^{-1} centroid blue-shift**
  - Larger than 1 kms^{-1} Doppler shift expected

- Blue-shift requires atmosphere close to the star to be even cooler than suggested by VLA data …

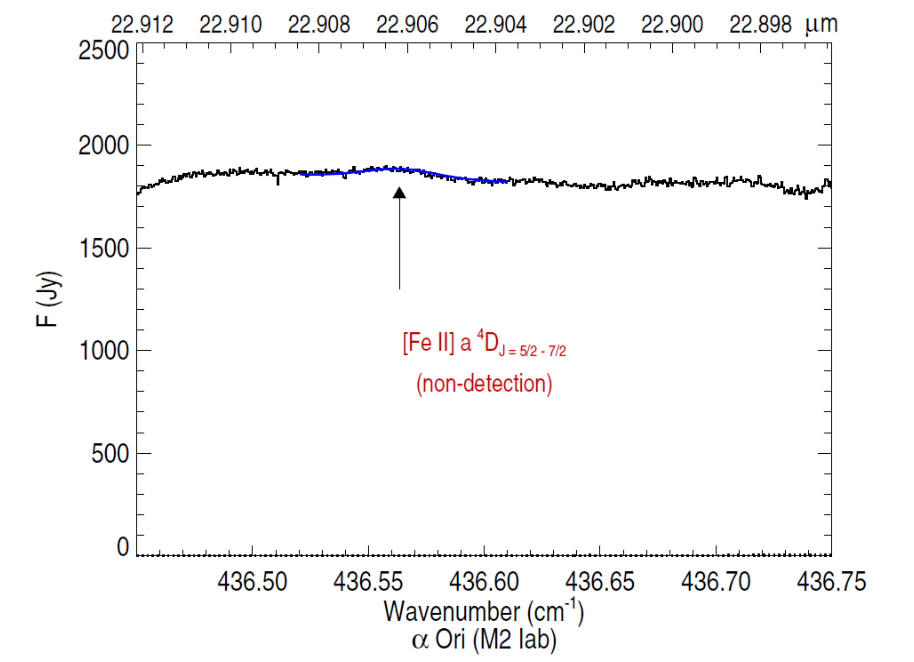


IRTF-TEXES [Fe II] 17.94 µm profile



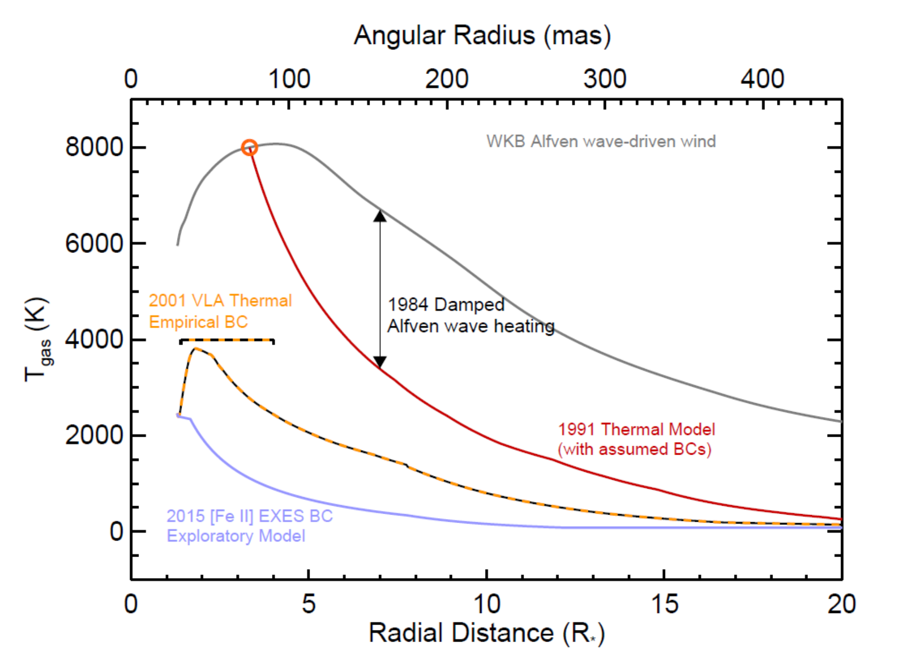
- T_{exc}=3,400 K
- Observed with TEXES on NASA's Infrared Telescope Facility
  - 2014 Feb 23 and Oct 22
  - 3m telescope optimised for IR
  - Mauna Kea 4200 m (14,000 ft)
  - R=50,000 (FWHM 6 kms^{-1})
- The line profiles are similar to those observed 10 years ago – very Gaussian
- Red-shift is at limit of wavelength error budget and may be real
  - Note it is opposite sense to 25.99µm

SOFIA-EXES [Fe II] 22.09 μm profiles



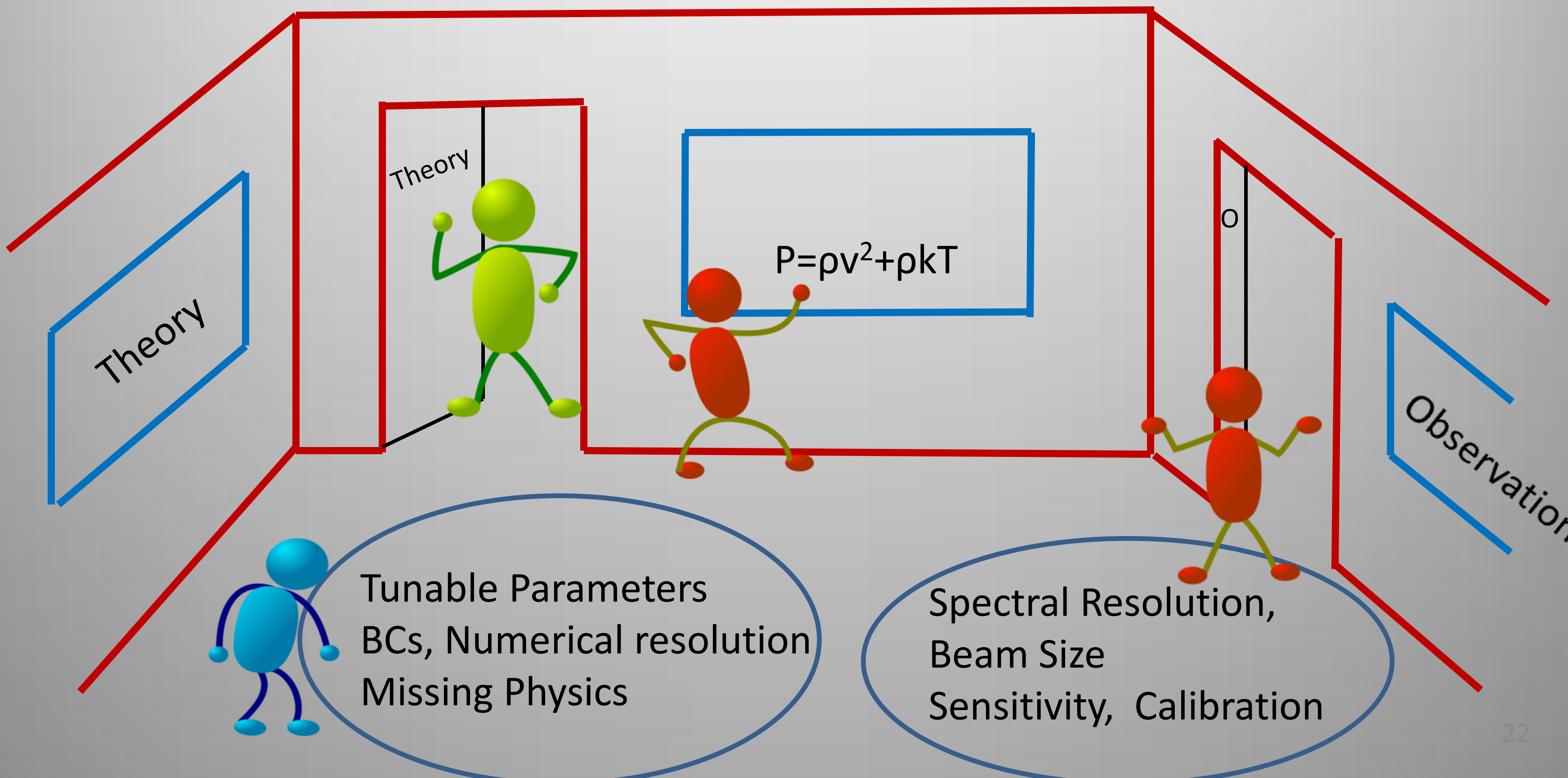
- T_{exc}=11,700 K
- Not detected on Betelgeuse or Antares
- Flux upper-limit 4x less than predicted from VLA constrained temperature model
- Flux limit consistent with the extra cooling required to produce the 25.99 μm blue-shift

Summary of EXES/TEXES study



- Observed [Fe II] 25.99 µm profile shows wind acceleration – modeling shows the flow is even cooler than expected (e.g., lower blue curve)
- Non-detection 22.290 µm consistent with cooler envelope
- 17.98 µm profiles similar to 10 yrs ago
- Previous theoretical cooling curves may be reconciled if they include
  - [Fe II] cooling - observed!
  - Complete adiabatic cooling

Wiggle Room



Theory
Theory
P=ρv²+ρkT
O
Observation
Tunable Parameters
BCs, Numerical resolution
Missing Physics
Spectral Resolution,
Beam Size
Sensitivity, Calibration

Some ideas – Final Slide

- Radio cm-continuum measures “brightness temperature” averaged over the beam
  - But atmosphere is a mix of hot and cold gas, what are we measuring?
- Radiation pressure effective on dust+molecules close in
  - but then they are destroyed – but why do we see distant rings?
  - Is dust just a tracer of episodic events
- Can we trust pulsation in models, if models don’t resemble know variability?
- Is the balance between magnetic pressure and heating different in weakly ionized plasmas (V. Airapetian, in progress) – less heating required?
- Geometry – magnetic flux tube divergence leads to additional cooling close to star
- Is the heating and cooling description complete enough?
  - For some reason Fe has been neglected, is that because it is too complicated - P. Woitke ?