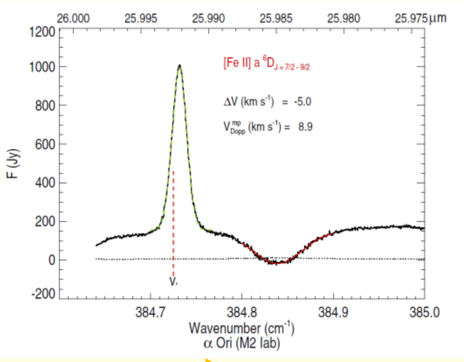
Testing Theoretical and Semi-Empirical Models of Red Supergiant Extended Atmospheres

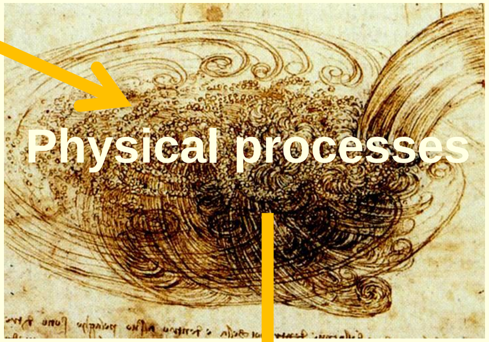
STellar End ProductS

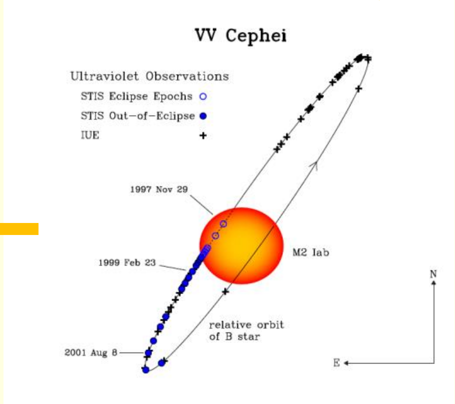
Graham M. Harper CU-CASA

Talk summary

SOFIA-EXES spectra



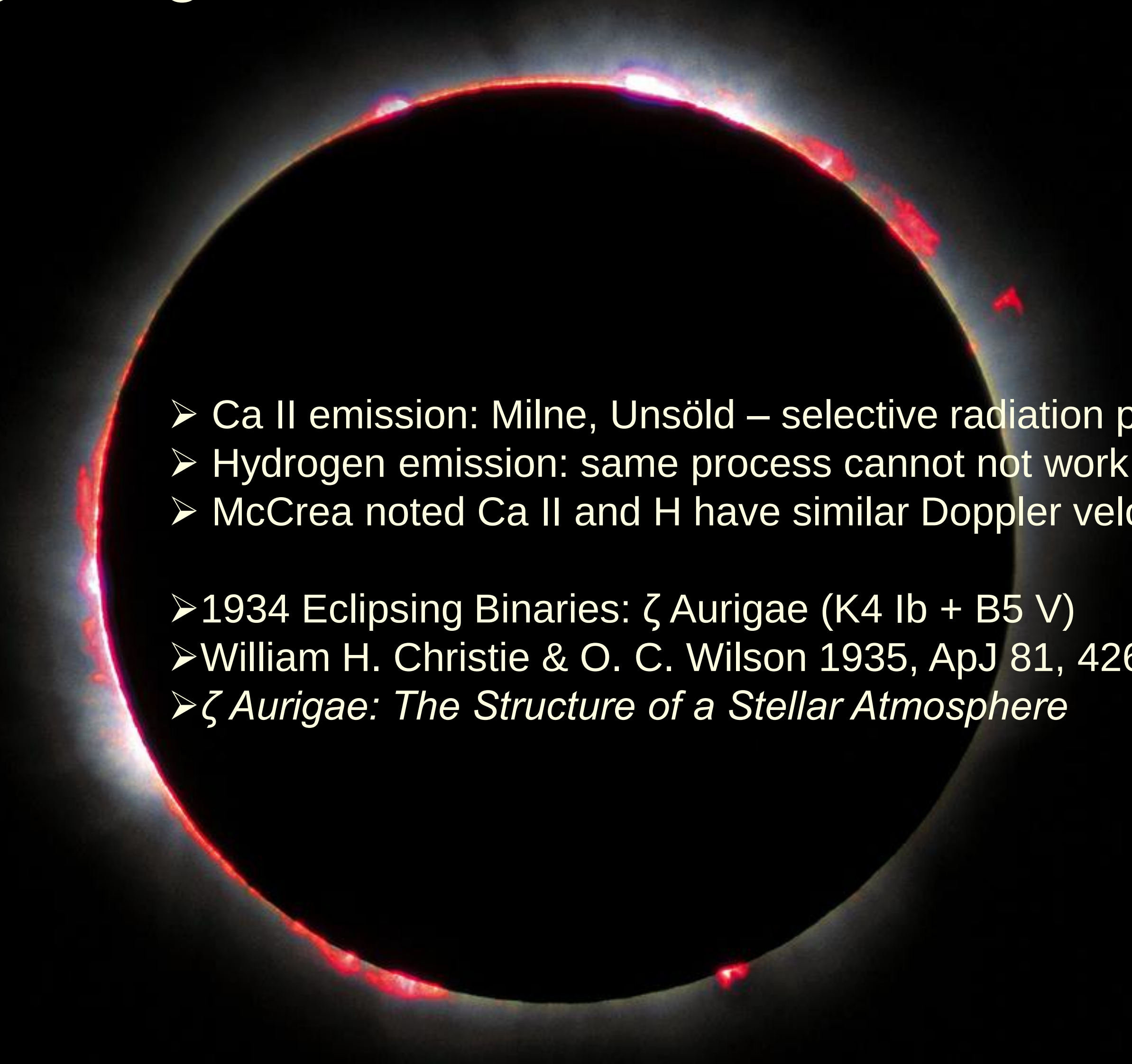




Tests of theoretical models

Seeking new constraints

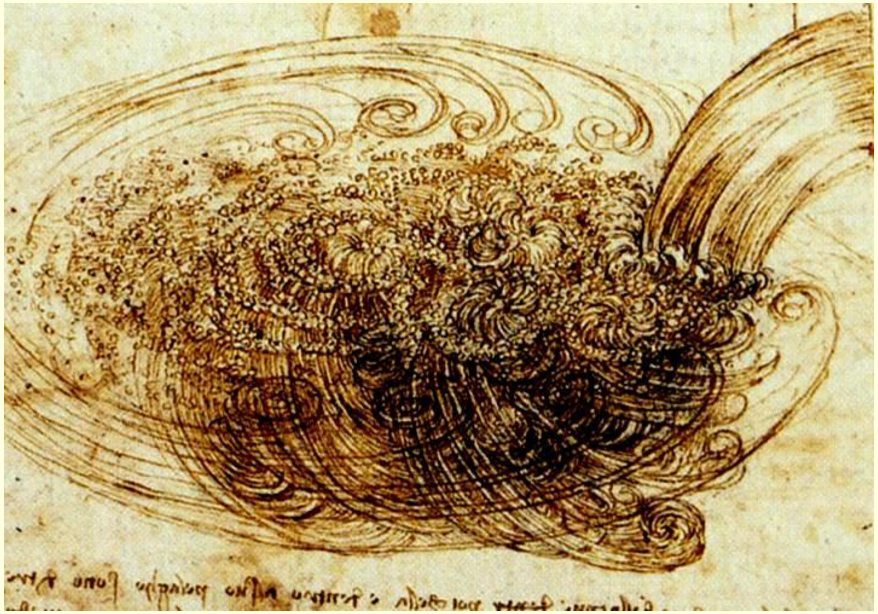
The beginning – circa 1930



- Ca II emission: Milne, Unsöld – selective radiation pressure
- Hydrogen emission: same process cannot not work
- McCrea noted Ca II and H have similar Doppler velocities

- 1934 Eclipsing Binaries: ζ Aurigae (K4 Ib + B5 V)
- William H. Christie & O. C. Wilson 1935, ApJ 81, 426
- *ζ Aurigae: The Structure of a Stellar Atmosphere*

Turbulence: δv - an important observational constraint



- Leonardo da Vinci ca. 1510

$$\mathrm{Re} = \frac{Interial}{Viscous} = \frac{\Delta \mathrm{v}\, \Delta L}{\nu} \approx 10^{11} \sim \mathrm{Re}_{mag}$$

[1] Chromospheres will be very well mixed - as observed

[2] Observed δv is a response to energy input, e.g. acoustic shocks, magnetic waves

[3] Spectroscopic measurement of δv important constraint – on energy input

Rosseland 1929 MNRAS 89, 49

McCrea, W. H. 1929 MNRAS 89, 718

The Physical “Steady” Problem: Momentum

$$\rho \mathrm{v} \frac{d\mathrm{v}}{dr} = -\rho\left[1 - \Gamma^{rad}_{pres}\right]\frac{GM_*}{R^2} - \frac{d}{dr}\left(P_{gas} + P_{wave}\right)$$

Acceleration: one reason we need spectrally resolved data

???

Too small to work

Measure this

$$P_{wave} = P_{turb} = \frac{C}{2}\rho\,\partial\mathrm{v}^2$$

Question: will a steady description ever work?

The Physical Problem: Energy Constraint

$$\dot{E} = \frac{\dot{M}}{2}\left(V_*^2 + V_\infty^2\right)$$

Terminal Wind Speed

Wind energy flux

Surface
Escape Speed

$$V(R_*) = 618\sqrt{\frac{M_*(M_{sol})}{R_*(R_{sol})}} \quad kms^{-1}$$

Observationally $V_*^2 >> V_\infty^2$

- Most of the energy goes into overcoming the gravitational potential – best place to study the mass loss physics is from the photosphere out to ~5 R* (SiO Masers)
- Early measurements: V_{oo} (accurate) and the mass-loss rates (poor).
- Need to measure the acceleration close to the star

Near Circumstellar Environment

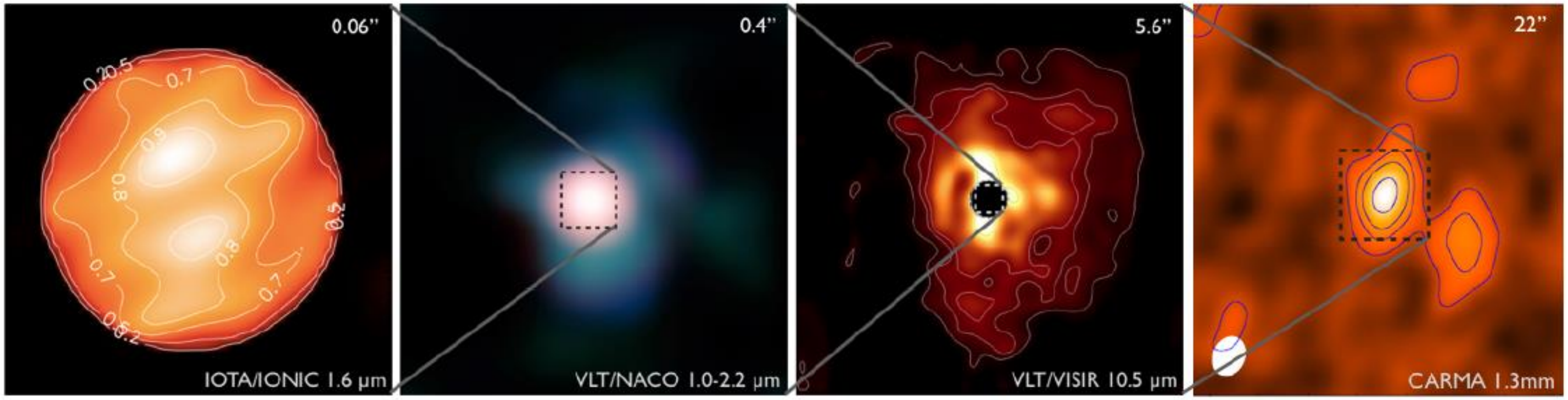


Figure 1: *1st panel:* interferometric image (H band, Haubois et al. 2009). *2nd panel:* NACO tricolor composite (RGB=KHJ) (Kervella et al. 2009). The CN molecule provides an excellent match to the absorption spectrum of the plume. *3rd panel:* VLT/VISIR image at 10.49 μm (Kervella et al. 2011). The ring-like structure at radius 0.5-1.0$''$ is probably related to the dust condensation radius. *4th panel:* CARMA interferometric image (O'Gorman et al. 2012). North is up, East to the left, and the field of view is given in the upper right corner of each image.

It is hard to test models when the details are not available … … some that have

- Time-independent models
  - linear Alfven waves
    - Hartmann & MacGregor 1980, 1982
  - non-linear Alfven waves
    - Charbonneau & MacGregor 1995
  - Weber-Davis rotating magnetic field (+dust)
    - Thirumalai & Heyl 2012

- Time-dependent models
  - 3-D RHD Convection & 1-D Pulsation
    - Arroyo-Torres et al. 2015
  - 1-D Acoustic waves (monochromatic, spectrum)
    - Cuntz 1990
  - non-linear and damped MHD waves (monochromatic, spectrum)
    - Airapetian et al. 2000 + 2015

Convection – fluffing the photosphere

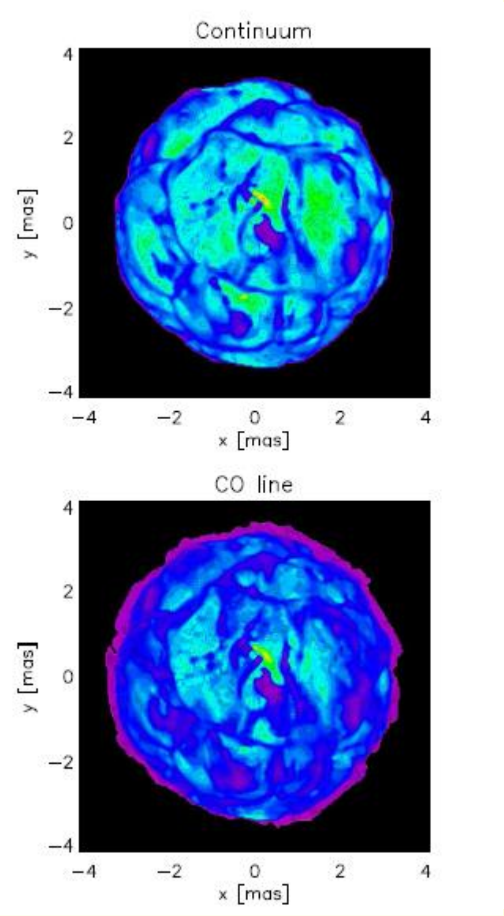
$$-\rho\left[1-\Gamma_{pres}^{rad}\right]\frac{GM_*}{R^2}=\frac{d}{dr}\left(P_{gas}+P_{turb}\right)$$

$$\left\langle P_{turb}\right\rangle=\frac{C}{2}\left\langle\rho\right\rangle\left\langle\partial\mathrm{v}^2\right\rangle\leq P_{gas}$$

- 3-D RHD models show 1-D models need extra pressure term, e.g.,Chiavassa et al. 2011 A&A 535; A22, Magic et al. 2013 A&A 557, A26; Tremblay et al. 2013 A&A 557, A7
- But 3-D models are still not as extended as *K*-band CO/continuum obs with the VLTI/AMBER: Arroyo-Torres, B. et al 2015 A&A 575, A50
- Something missing

Importance of δv long noticed for luminous low gravity stellar atmospheres, e.g., Nieuwenhuijzen & de Jager 1995 A&A 302, 811

Radial Pulsations



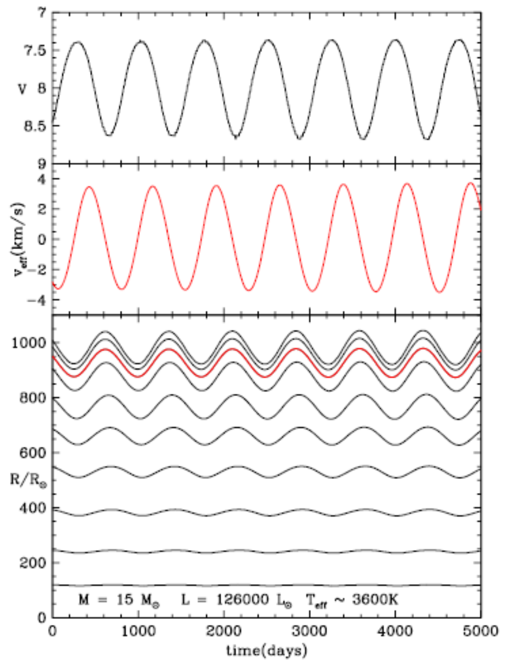
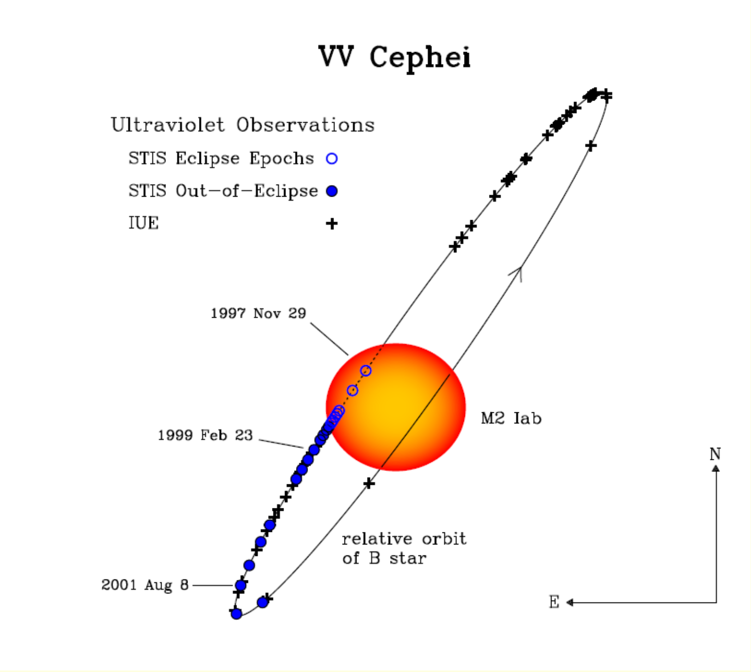


Fig. 16. Pulsation model of a RSG with M=15 M$_\odot$, L=126000 L$_\odot$, Teff~3600K. Bottom panel: Radius variation of selected mass zones in a pulsating supergiant model with M = 15 M$_\odot$ and L = 126000 L$_\odot$ (black curves). The red curve is the position of the photosphere (defined as the layer where the Rosseland optical depth equals 2/3). Middle panel: The velocity at the photosphere. Top panel: The visual light curve of the model, where the bolometric correction is obtained from the tables in Houdashelt et al. (2000a; 2000b).

- Arroyo-Torres, B. et al 2015 A&A 575, 50
  - VLTI-AMBER
  - Convection 3-D RHD
  - Radial pulsation

  - Pulsations may work for AGB stars but not for Betelgeuse-like stars
  - Non-radial pulsations?

Pairing eclipsing binaries with single spectral-type proxies



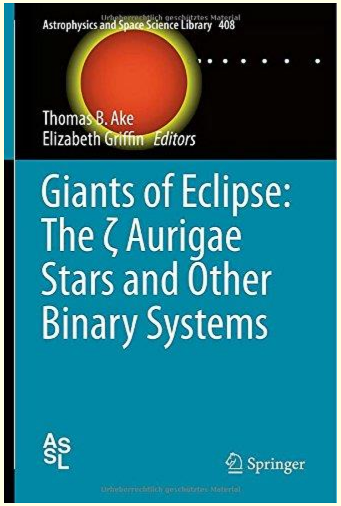
Bennett & Hagen Bauer 2015 Giants of Eclipse

VV Cephei (M2 Iab + B0-2 V)
Betelgeuse (M2 Iab)
† Antares (M1 Iab + B3 V)

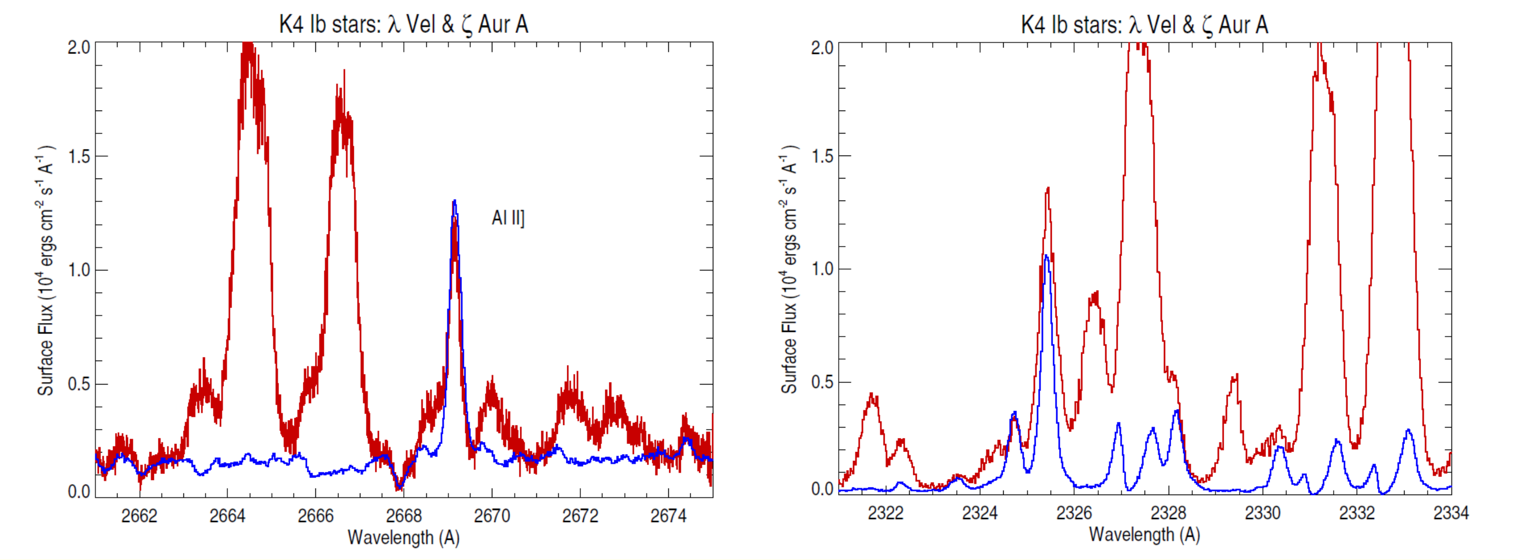
ζ (zeta) Aurigae (K4 Ib + B5 V)
λ Vel (K4 Ib)
† 32 Cyg 31 Cyg

Non-interacting binaries are suitable for extended chromosphere studies

- not so much for winds



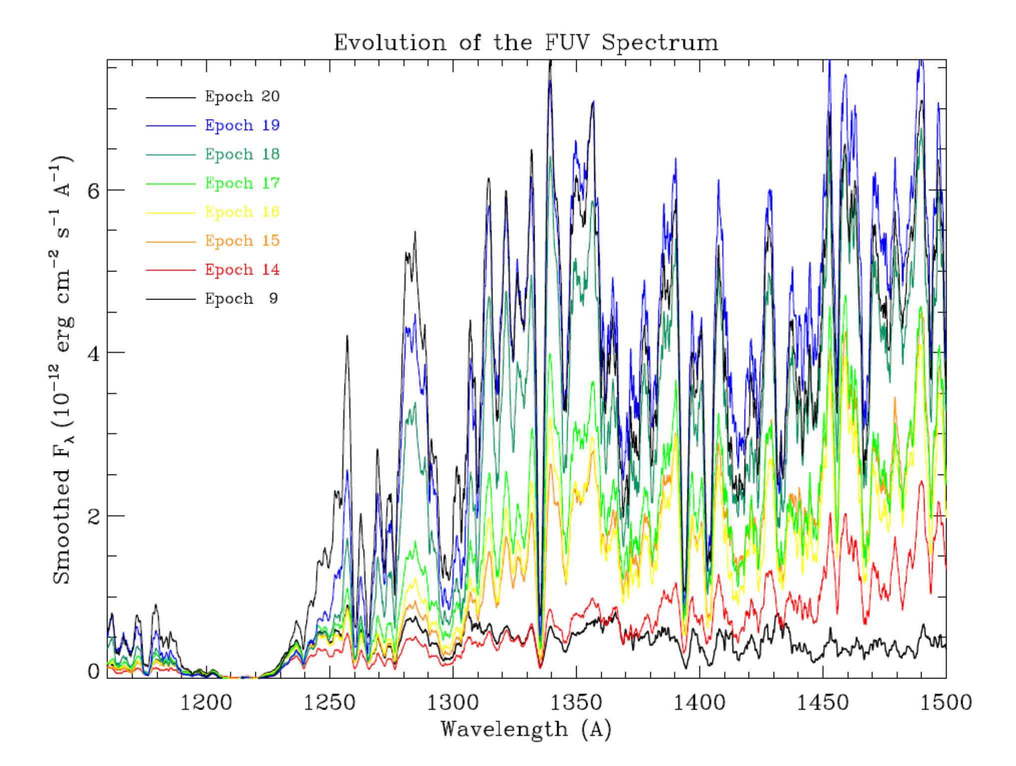
Matching spectral-types

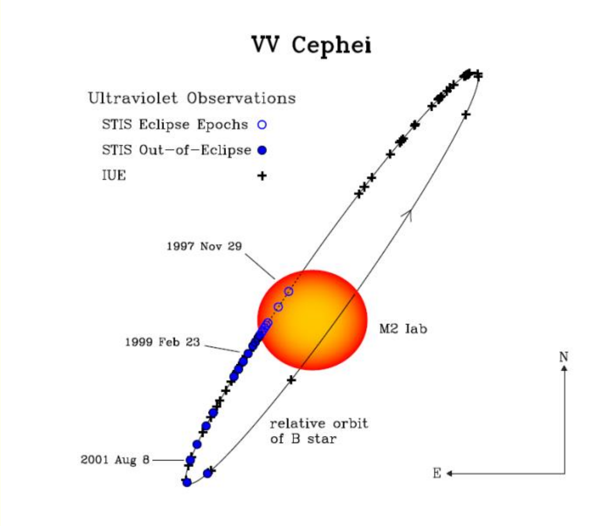


Eclipse spectra: K4 Ib star + scattered light ~ *tau* $^{0.4\text{-}0.5}$: Bennett (2006 ASP Conf. Ser., 348, 254)

ζ Aur chromospheric heating rates same as spectral-type proxies: Eaton (1992, MNRAS, 258, 473)

VV Cephei M2 Iab + B0-2 V

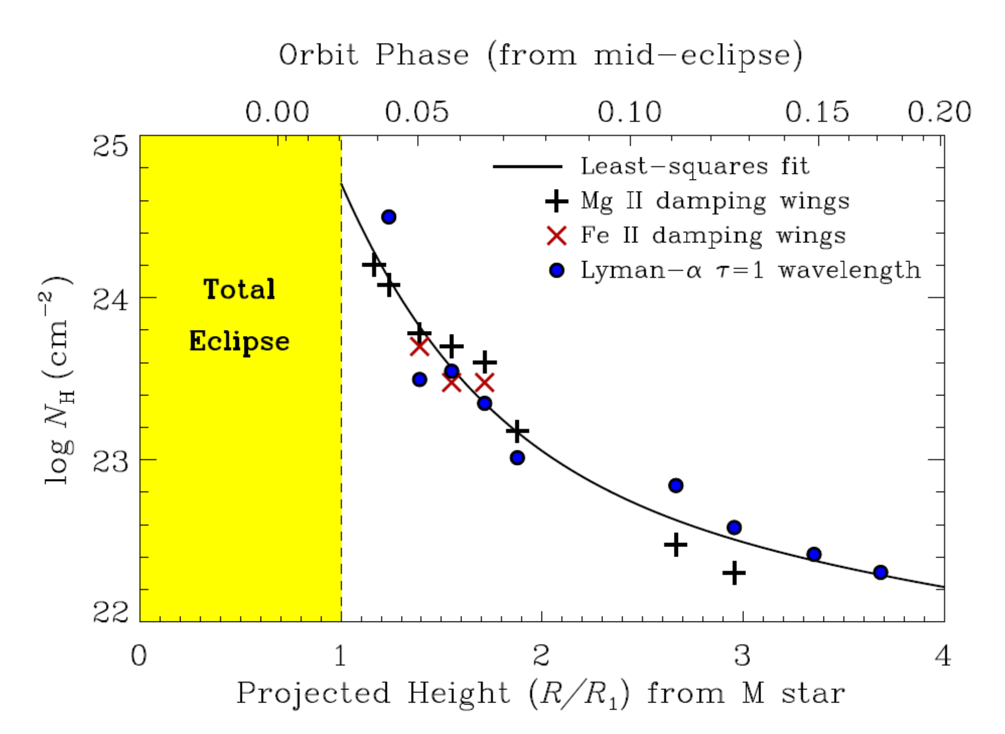




Damping wings of strong resonance lines provides column density through the atmosphere - independent of turbulence

Bennett & Hagen Bauer 2015

VV Cephei (M2 Iab + B0-2 V)



N_H = tangential hyd. column density
n_H = hydrogen density
H_ρ = density scale-height

$$n_H(R) = \frac{N_H(R)}{\sqrt{2\pi R H_\rho(R)}}$$

$$H(R) = n_H(R)\left(\frac{dR}{dn_H}\right)$$

Bennett & Hagen Bauer 2015 Giants of Eclipse

Thermal Continuum Tomography (TCT): Betelgeuse

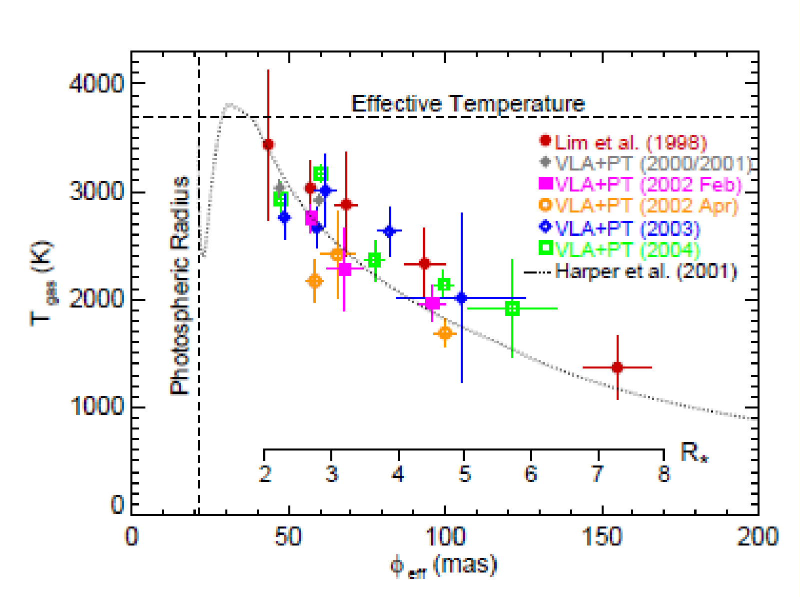
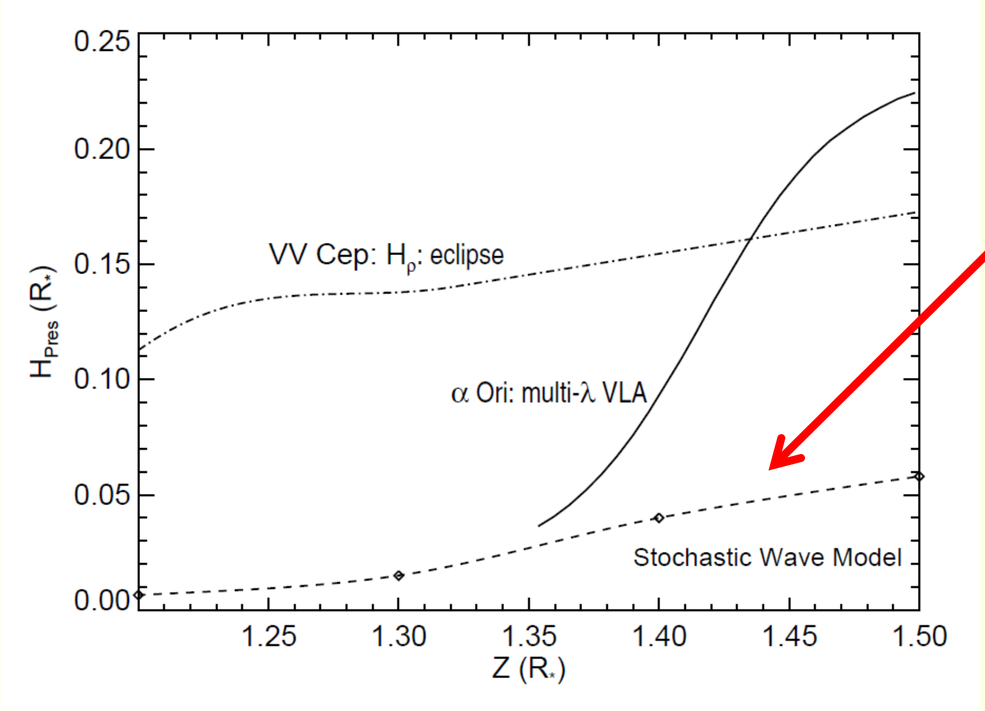


Figure Credit: O'Gorman E. et al. 2015 A&A, Accepted (arXiv:1506.07536)

Multi-λ spatially-resolved VLA continuum data: use TCT to build a self-consistent 2-D temperature-density model.

Note: Inner region requires higher frequency ALMA data to continue the mapping from 7mm to the photosphere

Time-dependent Acoustic Wave Models



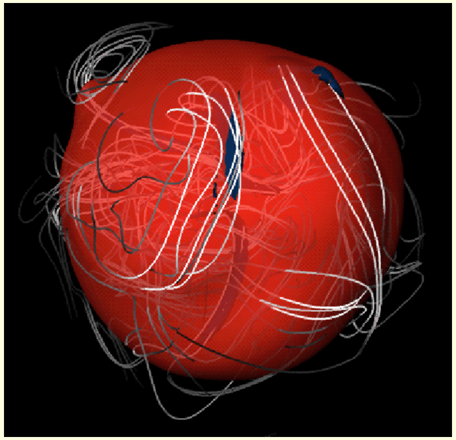
Photospheric convective motions generated acoustic waves

Predicted extension is much less than both empirical constraints for M2 Iab stars

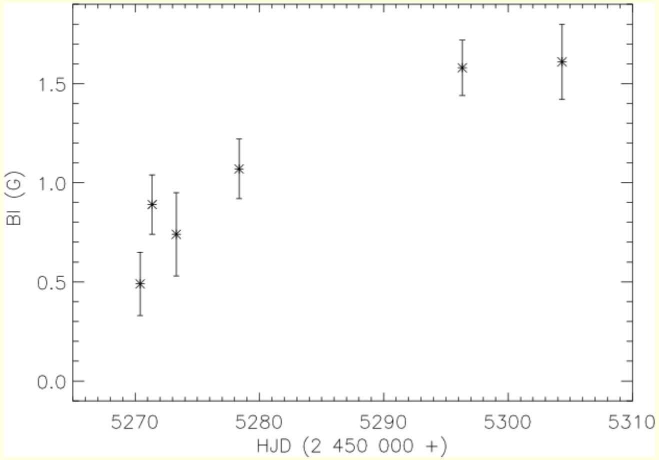
Acoustic models also known to fail to reproduce observed mass-loss rates

Cuntz, M. 1990 ApJ 349, 141

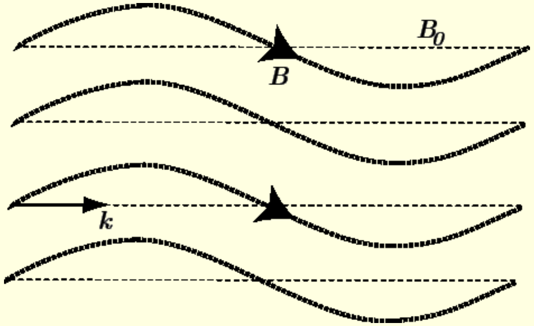
Magnetic Fields – Alfvén wave-driven winds



Localized B~100 G
Dorch, S.B.F 2004 A&A 423, 1101



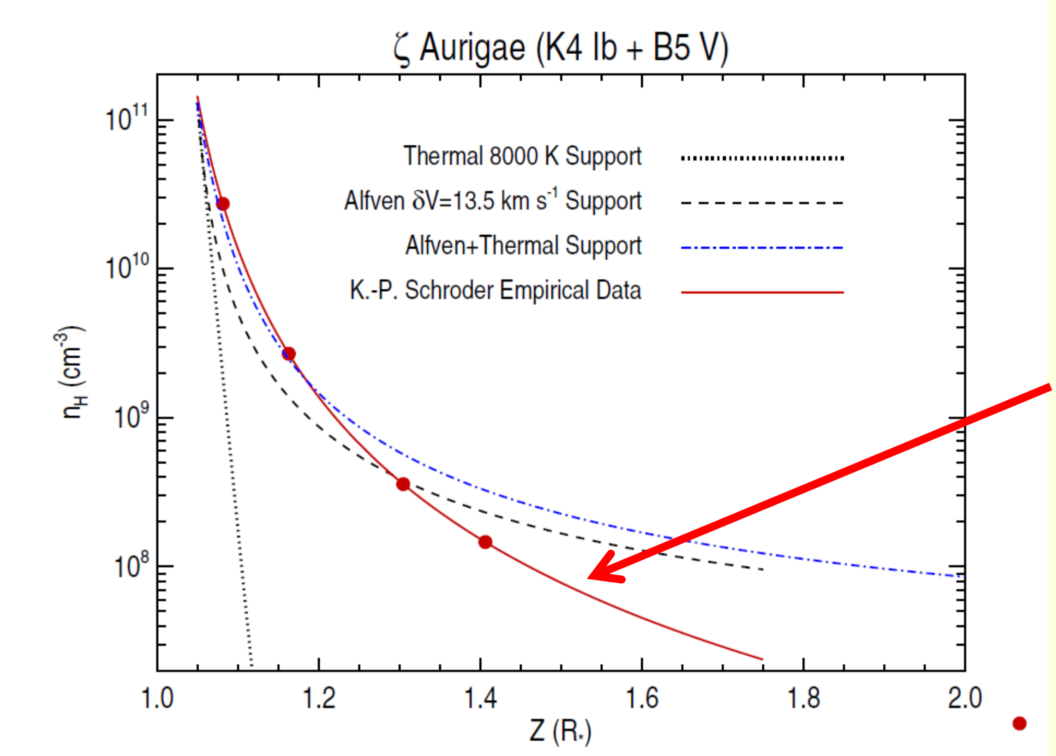
Betelgeuse: Aurière et al 2010 A&A 516, 2A



$$V_{Alf} = \sqrt{\frac{B^2}{4\pi\rho}} \qquad \partial V_{Alf} = \sqrt{\frac{\partial B^2}{4\pi\rho}}$$

$$-\rho\frac{GM_*}{R^2} = \frac{d}{dr}\left(P_{gas} + P_{Alf}\right) = \frac{d}{dr}\left(P_{gas} + \frac{\rho\left\langle \partial V_{Alf}^2 \right\rangle}{2}\right)$$

Alfvén wave-pressure support

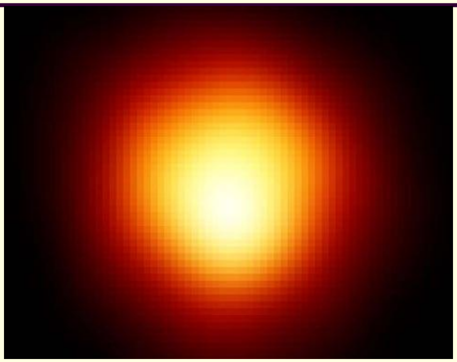


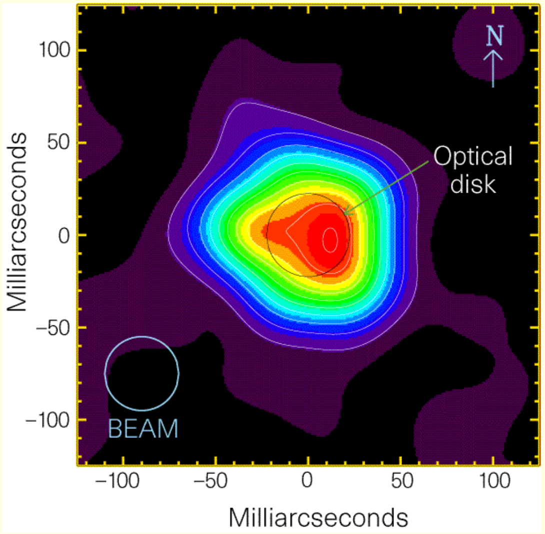
Observed difference implies wave reflection and/or damping

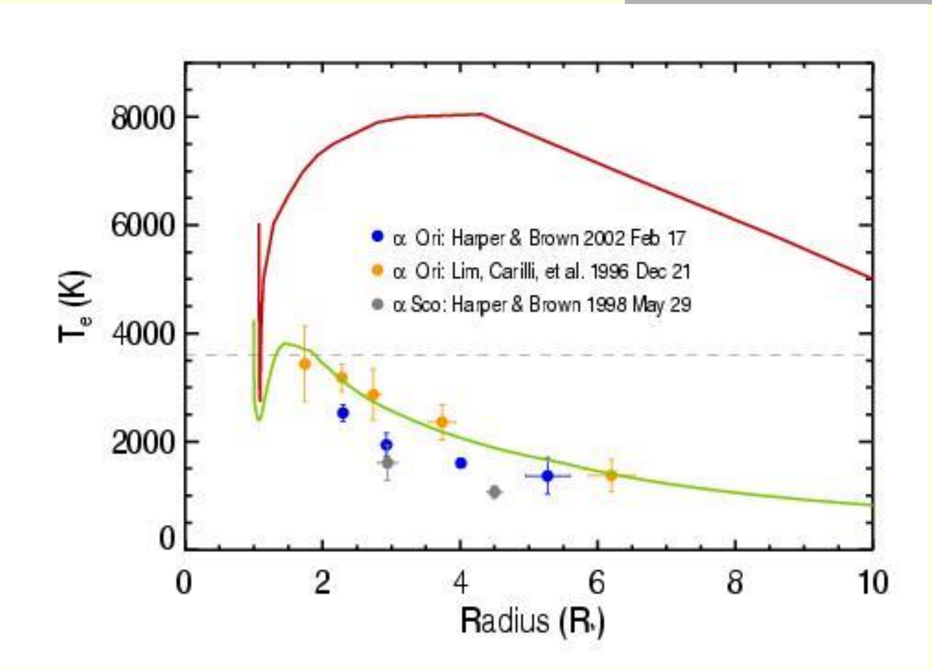
Schröder, K.-P. 1985 A&A 147, 103 (IUE analysis Fe II)

See Holzer, Flå, & Leer 1983 ApJ 275, 808 (Theory paper)

Betelgeuse: The problem with 1-D WKB Alfvén-wave driven winds

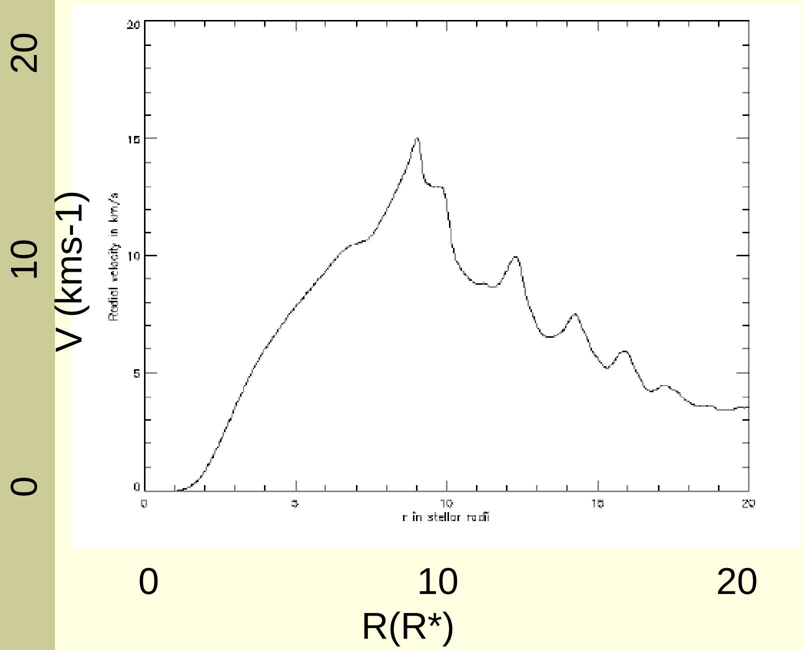






Need to damp the waves to avoid $V_{oo} >> V_*$
But this heats the wind, i.e., chromosphere
Lim et al VLA temperatures in conflict.

The rise and fall, and rise again of MHD models



- Time dependent non-linear MHD models (currently still no thermal predictions)
  - Damping and reflection included – not analytic
  - Capable of generating models with V_{oo} and mass-loss rates in right parameter space
  - Airapetian, V. S. et al. 2000 ApJ, 528, 965
- New generation of models that include weakly ionized winds
  - Airapetian et al. 2015 18th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (2014), eds. G. van Belle & H. Harris, p.269
- <u>But how do we test these models?</u>

Outflow acceleration in early-M Supergiants

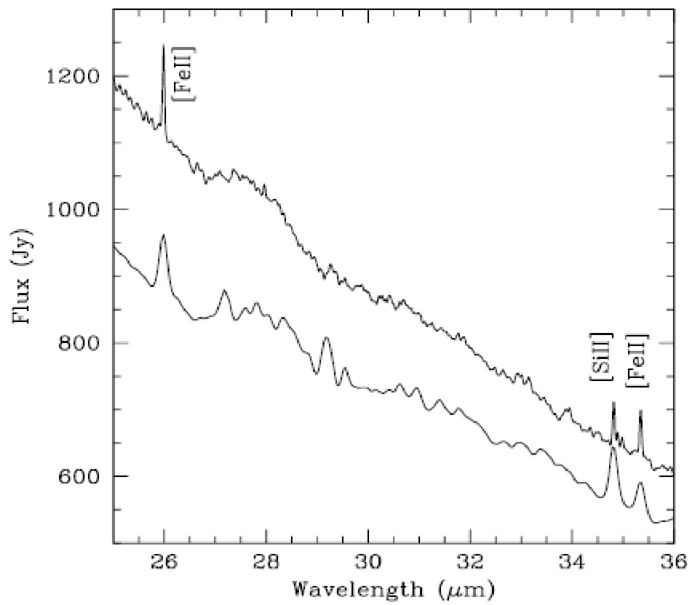
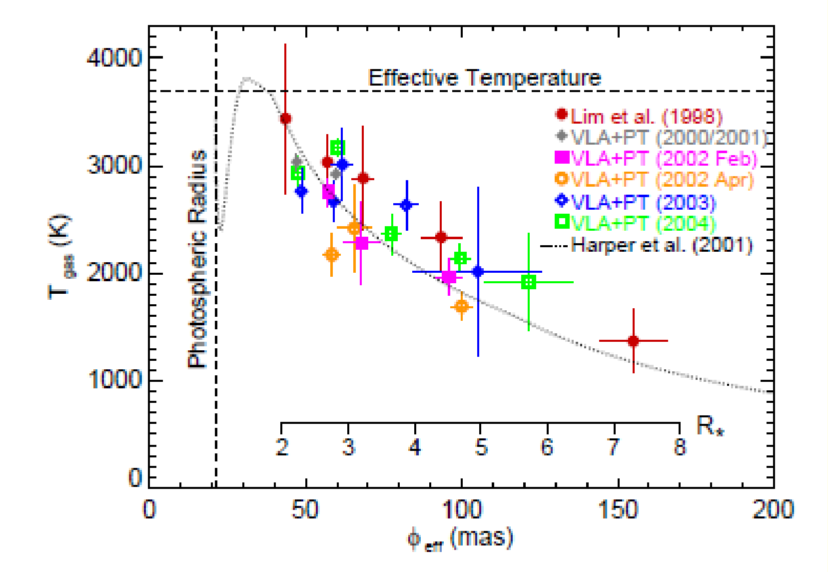


Fig. 1. Grating spectra of α Ori (*top*) and α Sco (*bottom*) showing the three atomic fine-structure lines. Note that the flux for α Sco has been multiplied by 1.6 in this plot.

Justtanont, K., Tielens, A.G.G.M., de Jong, T., Waters, L.B.F.M, & Yamamura, I. 1999 A&A 345, 605

ISO-SWS
α Ori (M2 Iab) R=1000
α Sco (M1 Iab) R=250



O'Gorman E. et al. 2015 A&A, Accepted (arXiv:1506.07536)

Forbidden Fe II Ladders

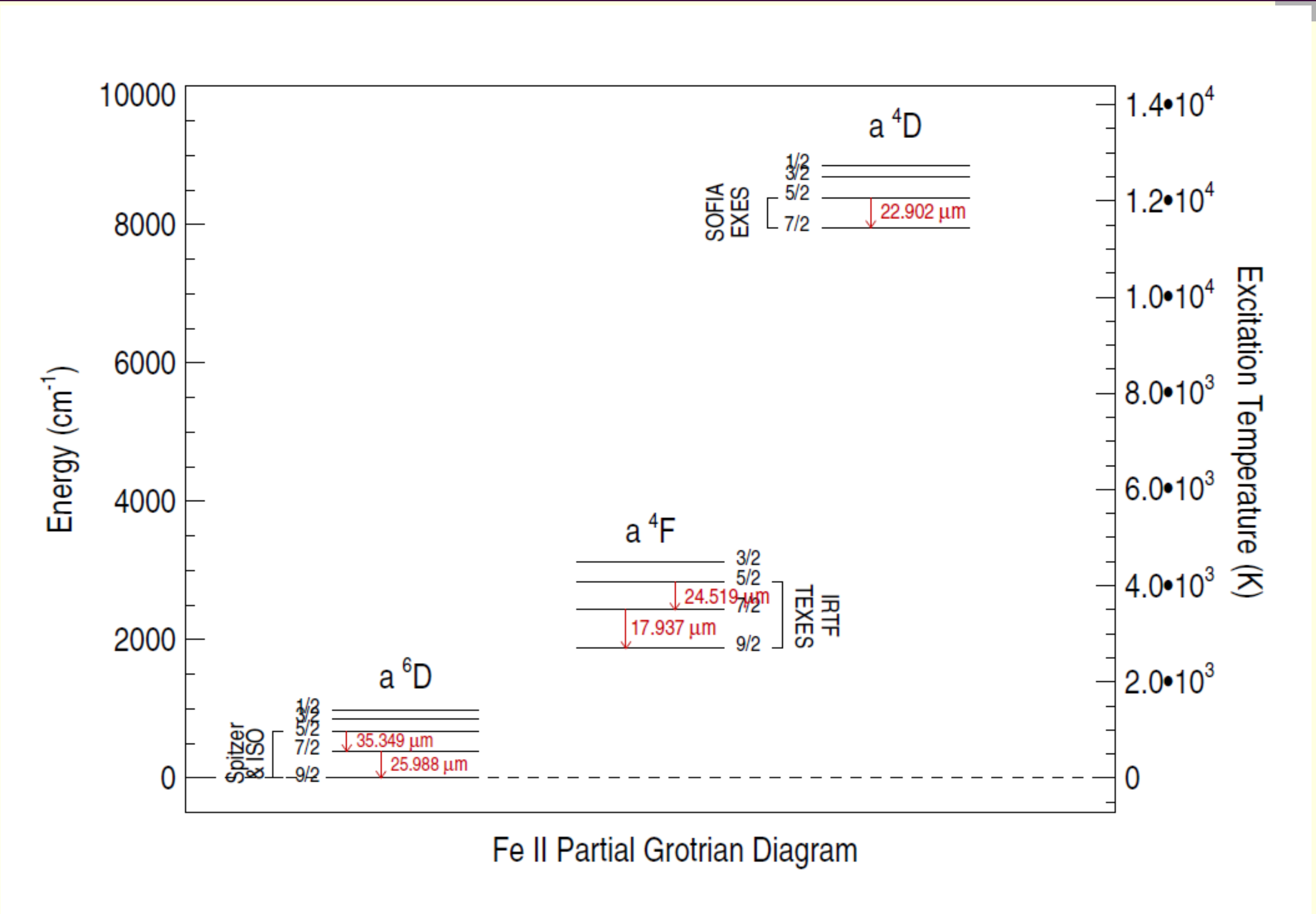
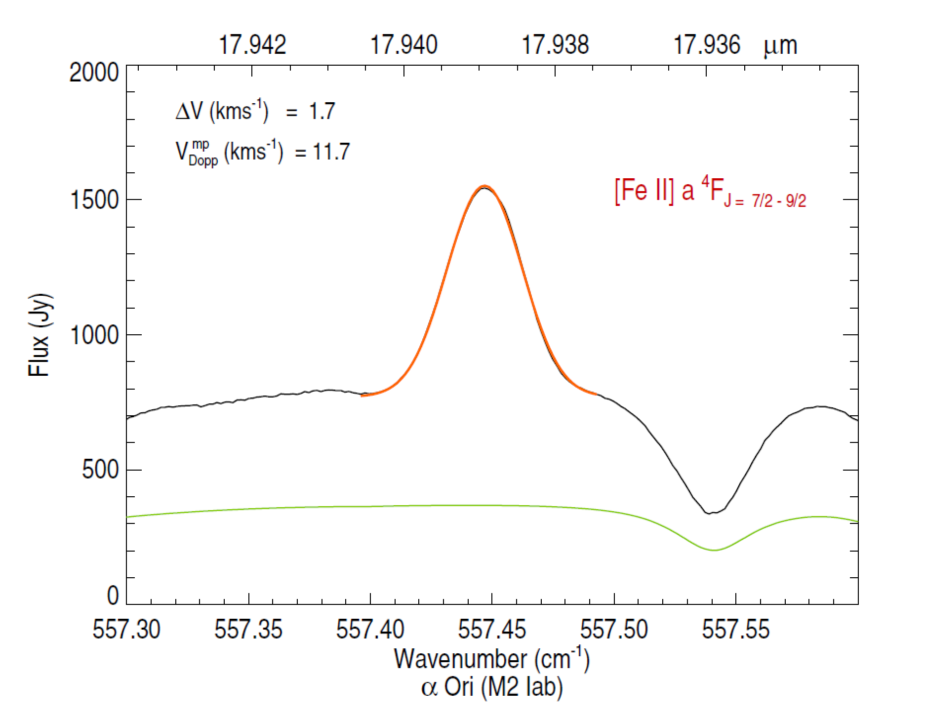
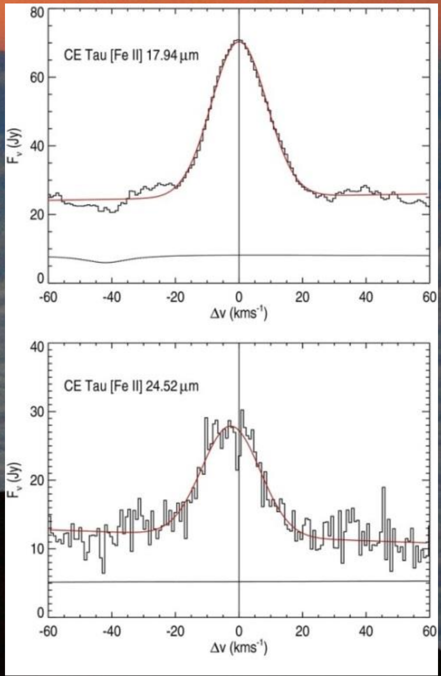


Image Credit: Taylor S. Chonis © 2015





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 747-SP + EXES (Commissioning + Cycle 2 spectra)

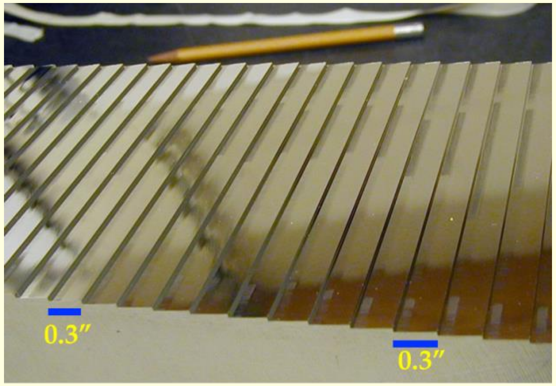
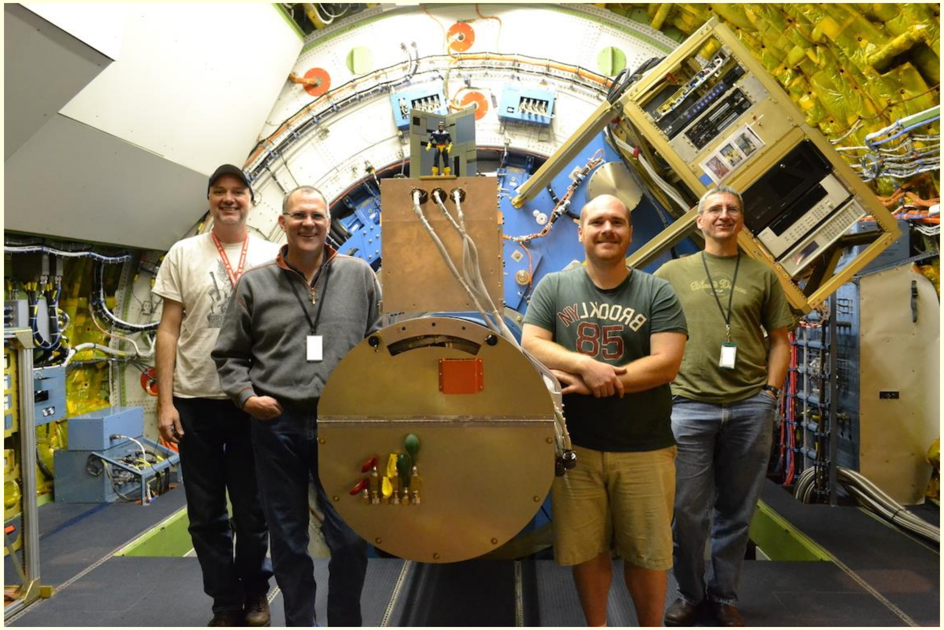


Photo credit: NASA /Jim Ross

Feb/March 2015 Commissioning Flights of EXES
Echelon-cross-Echelle Spectrograph

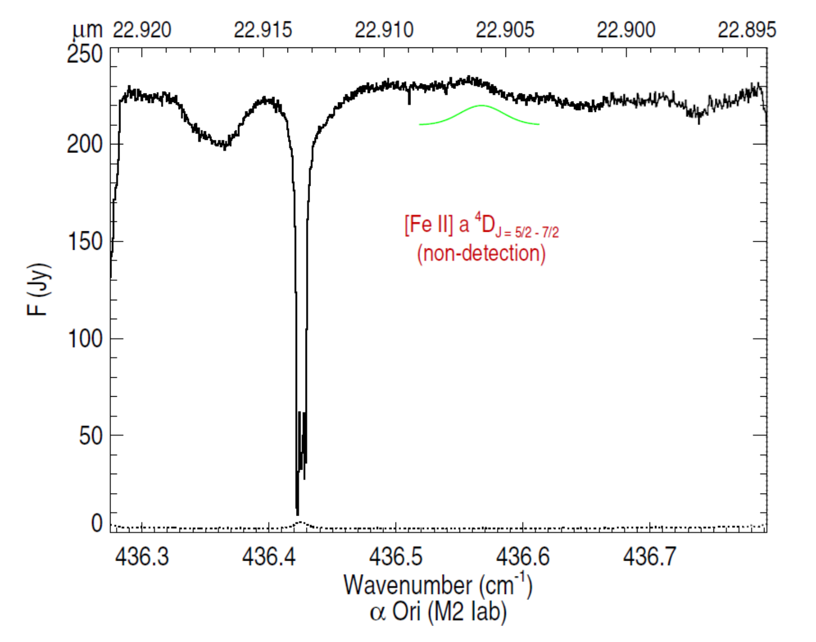


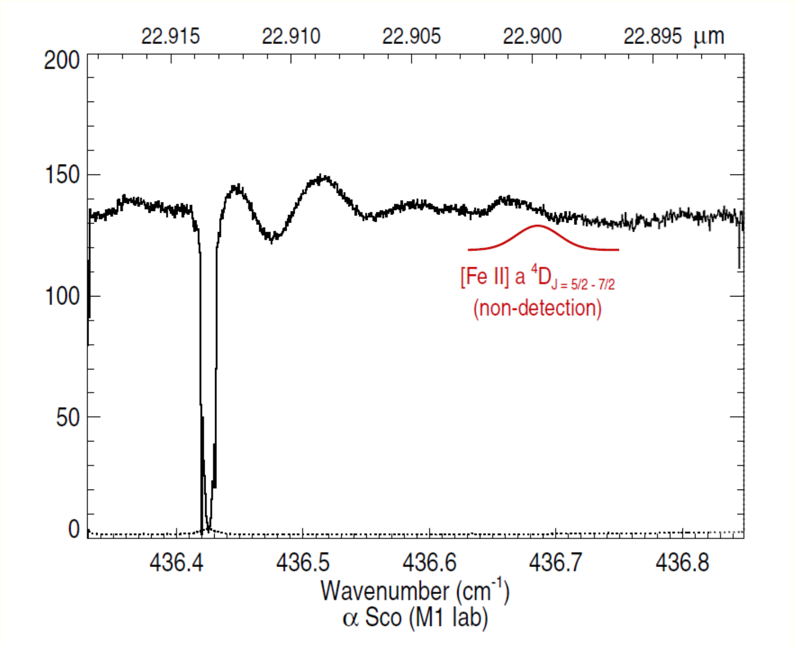
R ~ 100,000 @ 4.5-10 mic
R ~ 50,0000 @ 28 mic

1024x1024 Si:As detector array

- EXES Instrument Team: Matt Richter (UCD - PI), Mark McKelvey (Ames - Co-PI), Mike Case (UCD - Software Engineer), Curtis DeWitt (UCD)

[Fe II] 22.90 μm – a $^4D_{J=5/2-7/2}$

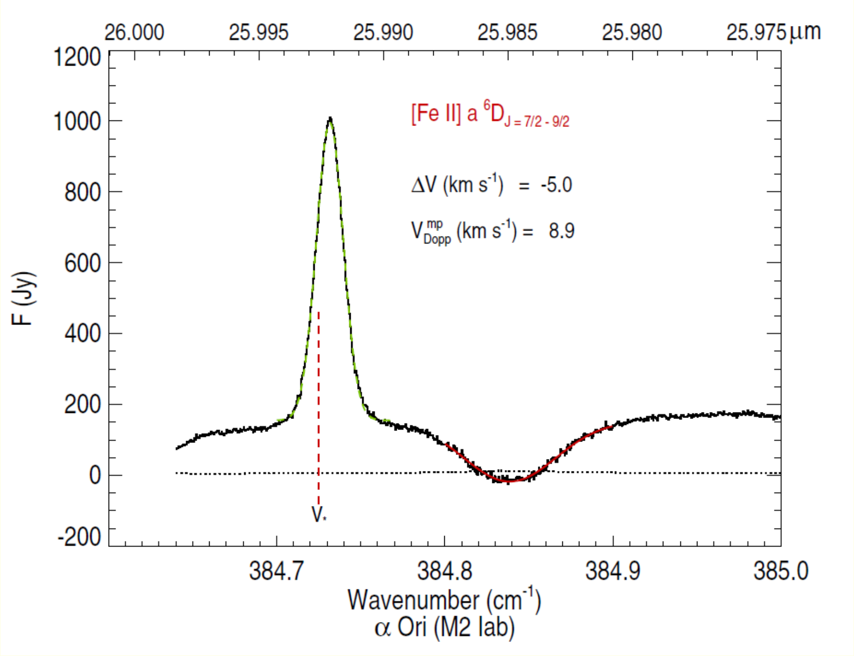


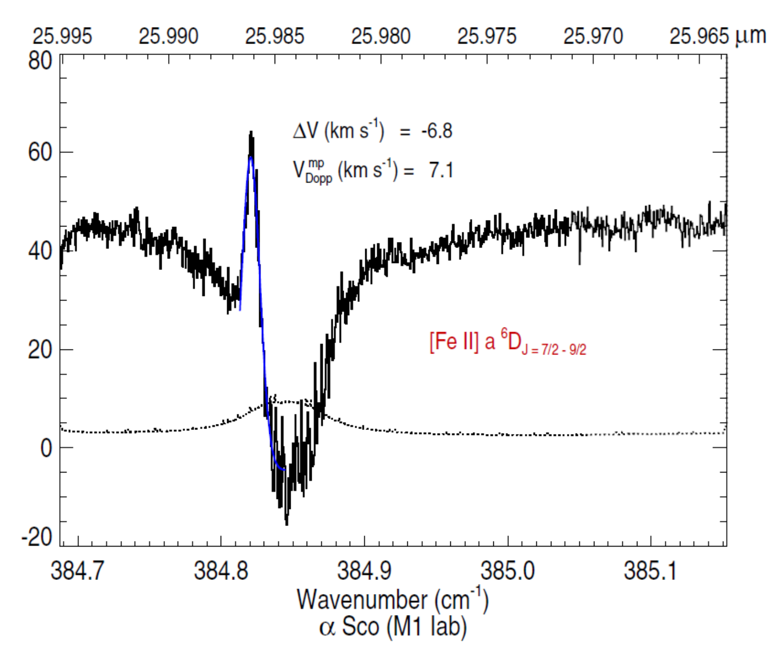


Non-detection of [Fe II] 22.90: powerful constraint on amount of warm chromospheric+CS material

Cycle 2 (Harper, Richter, Curtis, O'Gorman, & Guinan) + Commissioning (EXES Science+Instrument Team)

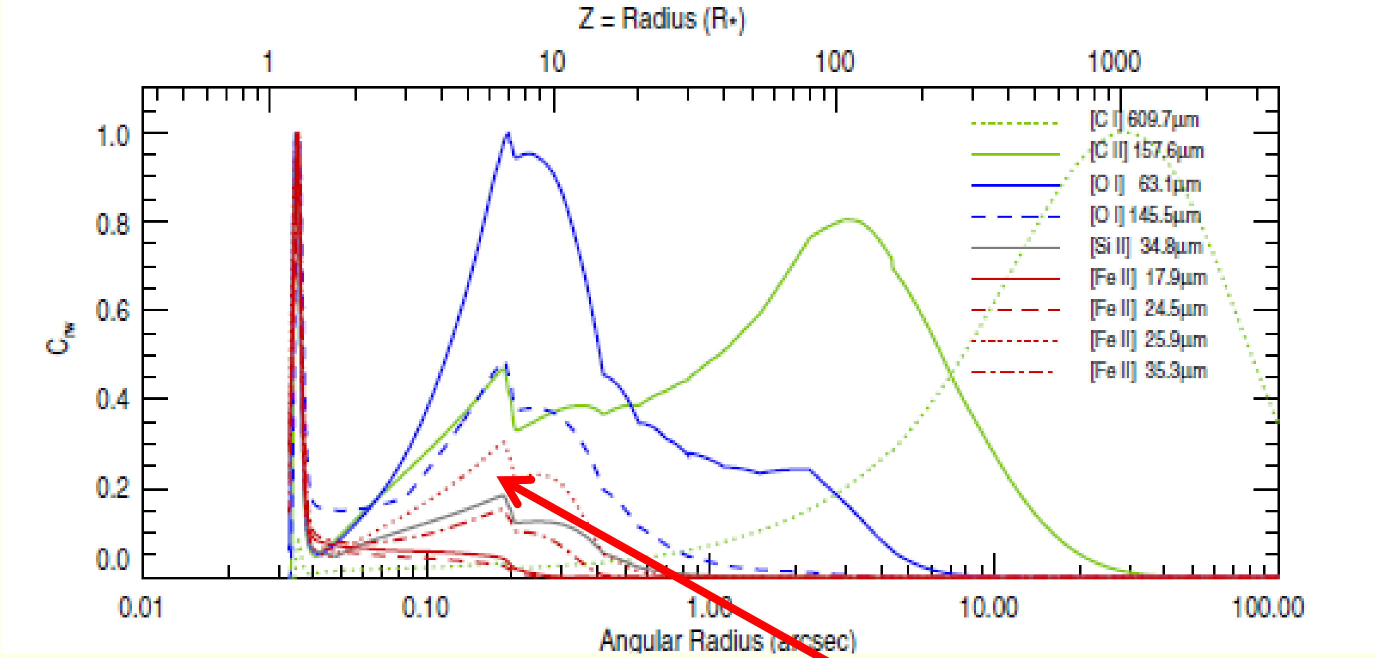
[Fe II] 25.99 µm – a $^6D_{J=7/2-9/2}$





Now see the CS outflow, combined with turbulence

Formation Radii

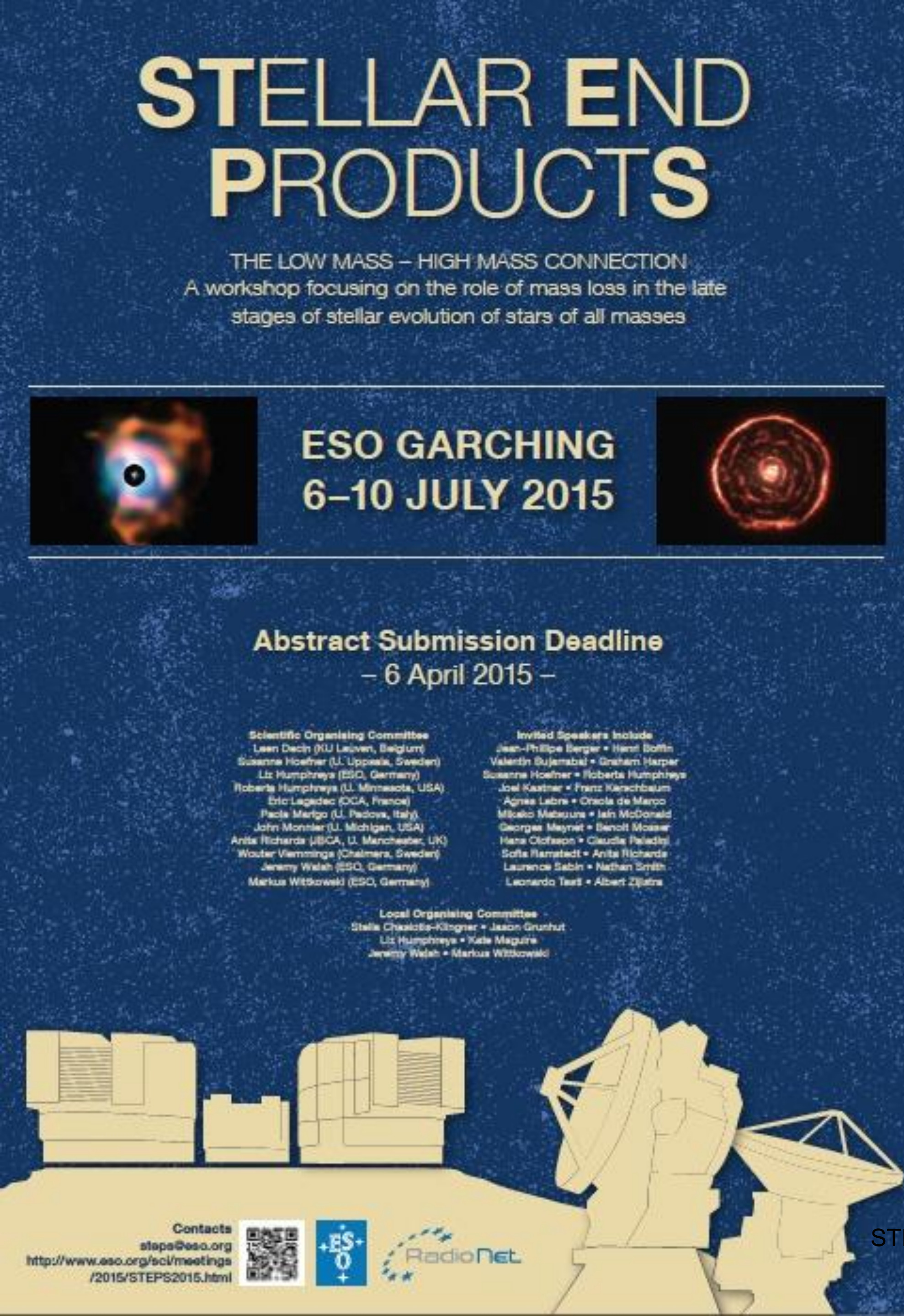


Harper et al. 2009 ApJ 701, 1464

Out flow detected < $10R_*$

Summary

- Stress importance of spectral resolution for measuring flows (outflow and turbulence) in wind acceleration zone
- Coordinated efforts to observe zeta Aurigae systems and their spectral-type proxies.
  - Maximum transference of zeta Aur information to single evolved cool stars
  - Establish just how similar zeta Aur primaries are to single stars
- SOFIA: challenge MHD models for K and M supergiants
- ALMA: refine M supergiant T_{gas}-ρ models between the photosphere and region probed by the VLA (including the extended molecular emission



Enjoy the workshop!