Probing the Thermodynamics of Red Giant Mass Outflows with the JVLA

Eamon O'Gorman
Trinity College Dublin, Ireland

Graham Harper, Anita Richards, Steve Drake, Alex Brown

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Outline

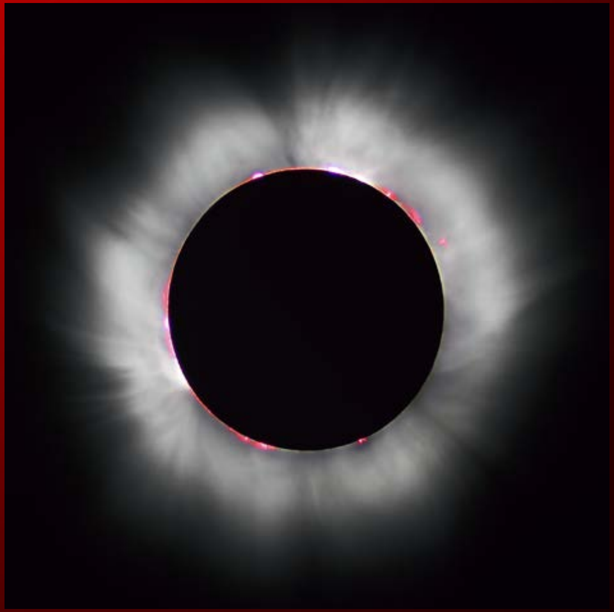
- Red Giant Outflows
- Red Giant Radio Emission
- Sample Selection
- JVLA Observations
- Observing Strategy
- Results
    - α Tau
    - α Boo
- Spectral Energy Distributions
- Hydrogen Ionization Code
- Conclusions & Future Work

JVLA, June 2012

Red Giant Outflows

Late-type red giants:
- chromosphere is always present
- coronal emission diminishes
- cool massive wind kicks in (e.g. Linsky & Haisch, 1981; Ayres et al., 1997)
- Relatively dense and slow moving winds

$$V_{terminal} < V_{escape}$$



Solar Eclipse

Importance:
- Enrich the interstellar medium with material required for the next generation of stars and planets
- Mass loss can alter the evolutionary fate of a star

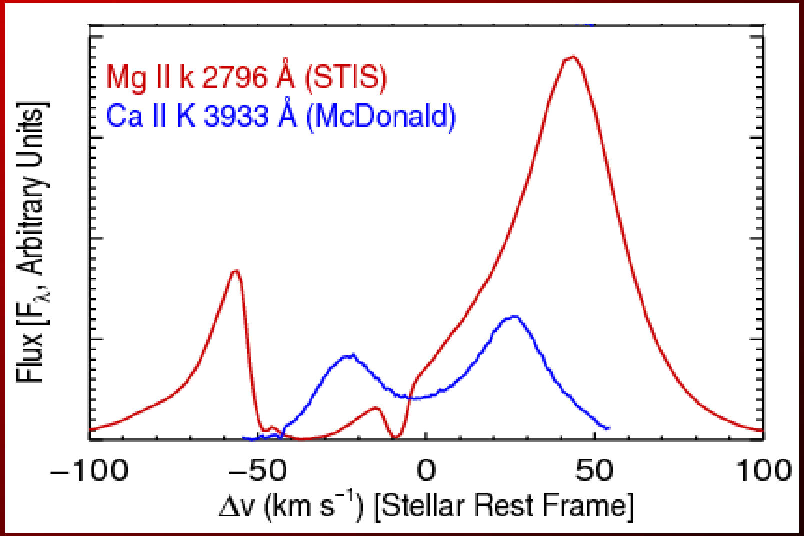
Wind Driving Mechanism:
- An enduring mystery! (Holzer & MacGregor, 1985)
- Insufficient molecular or dust opacity
- Mass-loss rates too large for acoustic/pulsation models (Sutmann & Cuntz, 1995)
- Absence of hot wind plasma in optical & UV data – too cool to be Parker type flows

Red Giant Radio Emission

- Wind & chromospheric properties (dM/dt, v_{ter}) generally determined by analysing strong chromospheric resonance lines.

- Thermal structure poorly constrained. Very sensitive to T ($h\nu/kT >> 1$).

- At cm/mm the thermal continuum (Planck) function depends linearly on T.



α-Boo: Blue-shifted absorption component->outflow

- Continuum flux measurements at cm/mm wavelengths can probe different different layers in the atmosphere as radio opacity is proportional to ~ $\lambda^{2.1} n_e n_{ion}$.

- Multi-frequency observations at cm/mm wavelengths allow us to get spatial information from point sources!

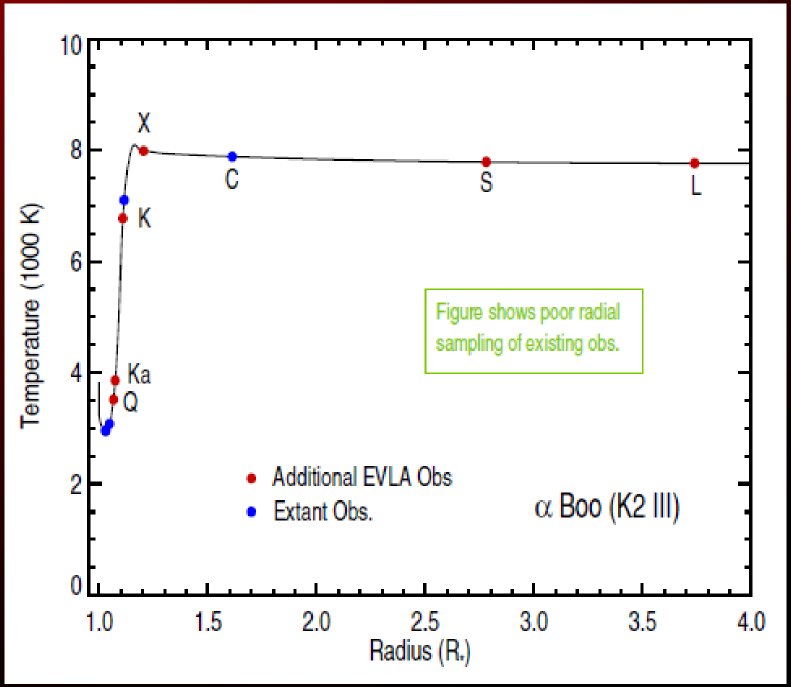
- Importance: T controls the level populations & ionization balance. Required for a detailed analysis of the wind thermal balance. Clues to mass-loss mechanism.

Sample Selection

Goal: *Observe two 'standard' red giants at all possible JVLA frequencies allowing the temperature to be probed throughout the wind acceleration zone (~1 – 4 R_*) in each.*

Arcturus (α Boo: K2 III) and Aldebaran (α Tau: K5 III)

- Single, non-dusty and non-pulsating
- Nearby (~ 11 pc and 20 pc)
- Well known stellar parameters
- Semi-empirical 1-D chromospheric and wind models that can be directly tested



JVLA Observations

Open Shared Risk Observing (OSRO)
B configuration – February 2011
Bandwidth = 256 MHz (2 spw's @ 64 x 2 MHz); Full Polarization

α Boo: S – Q-band in ~9 days (13th Feb 2011 - 22nd Feb 2011)
α Tau: S – Q-band in ~2 days (11th Feb 2011 - 13th Feb 2011)

A unique Data Set
α Boo: L-band not commissioned
α Tau: L-band not requested

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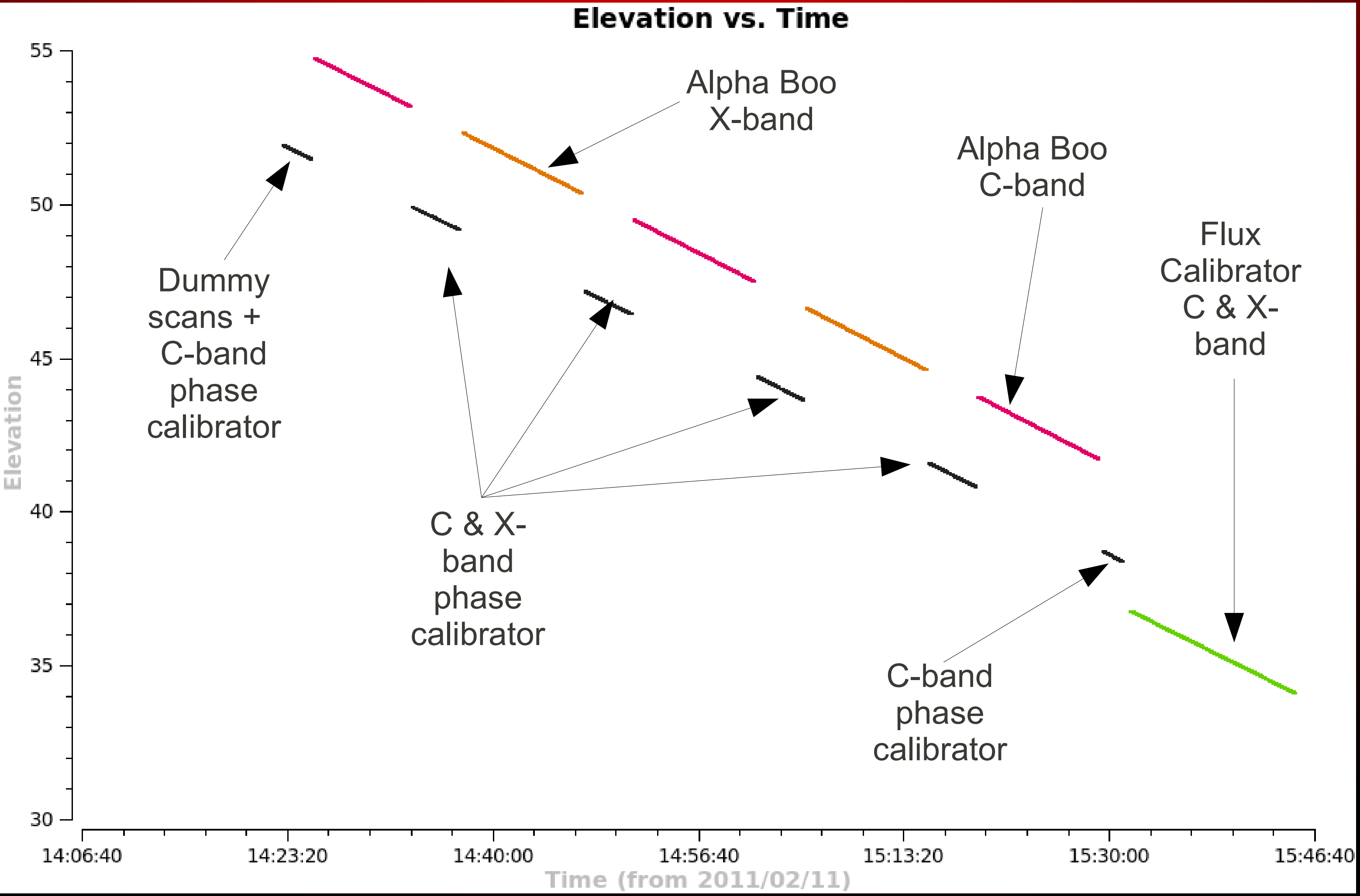
Directors Discretionary Time (DDT)
B configuration – July 2012
α Boo
L Band: Bandwidth = 1 GHz (16 spw's @ 64 x 1 MHz); Full Polarization
S Band: Bandwidth = 2 GHz (16 spw's @ 64 x 2 MHz); Full Polarization

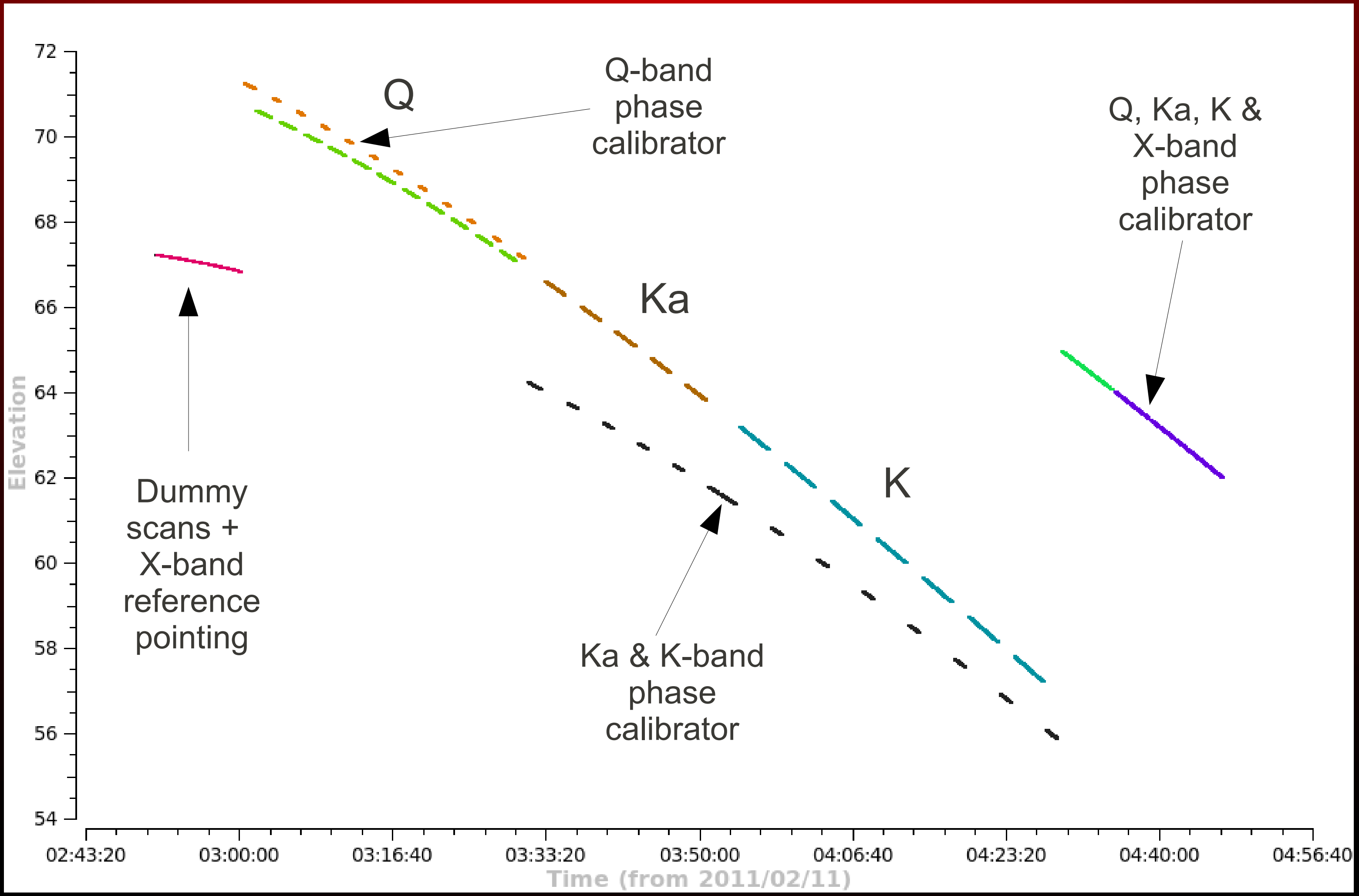
Observing Strategy *– Low Frequencies*

11 Feb 2011: Alpha Boo: C & X-bands: 1.5 Hr Track



Observing Strategy *– High Frequencies*

11 Feb 2011: Alpha Tau: K,Ka & Q-bands: 2 Hr Track

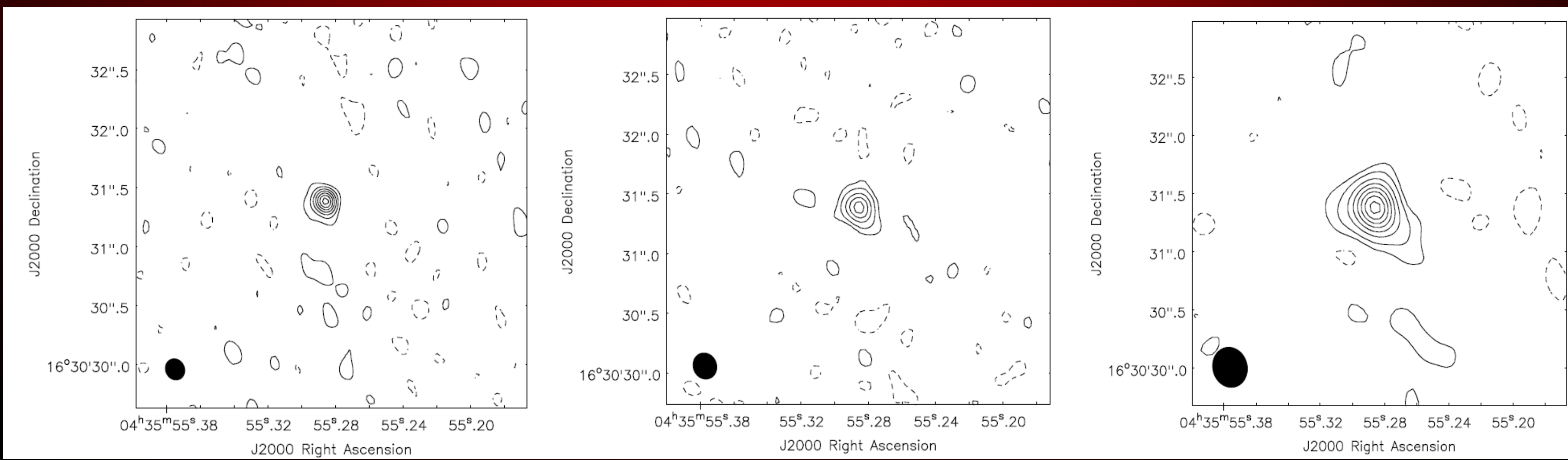


Results: α Tau – *High Frequencies*

Q-band (43 GHz)
S_ν = 3.67 mJy

Ka-band (34 GHz)
S_ν = 2.19 mJy

K-band (22 GHz)
S_ν = 1.86 mJy



Contours = (-2,2,4......14)xσ
σ = 240 μJy

Contours = (-2,2,5,10,15,20)xσ
σ = 96 μJy

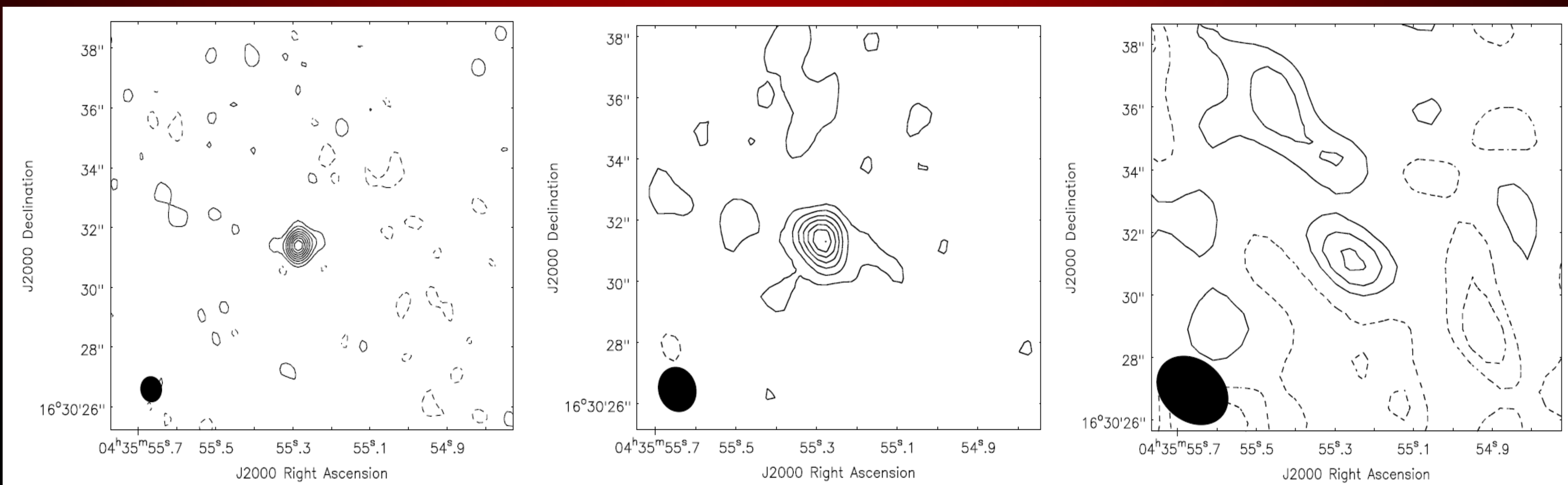
Contours = (-2,2,5,10,....35)xσ
σ = 50 μJy

Results: α Tau – *Low Frequencies*

X-band (8 GHz)
S_ν = 0.3 mJy

C-band (5 GHz)
S_ν = 0.15 mJy

S-band (3 GHz)
S_ν = 0.06 mJy

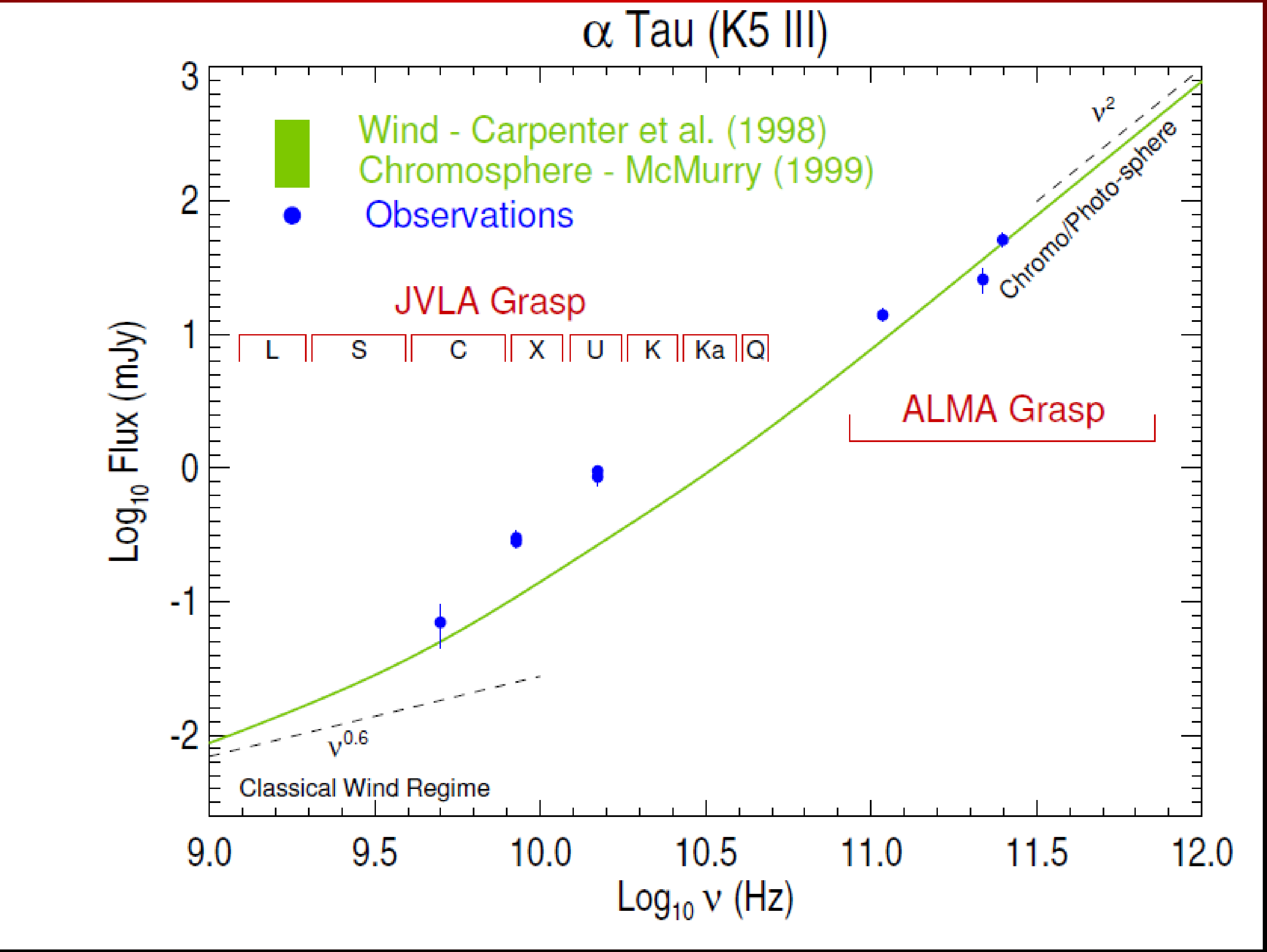


Contours = (-2,2,4......16)xσ
σ = 16 μJy

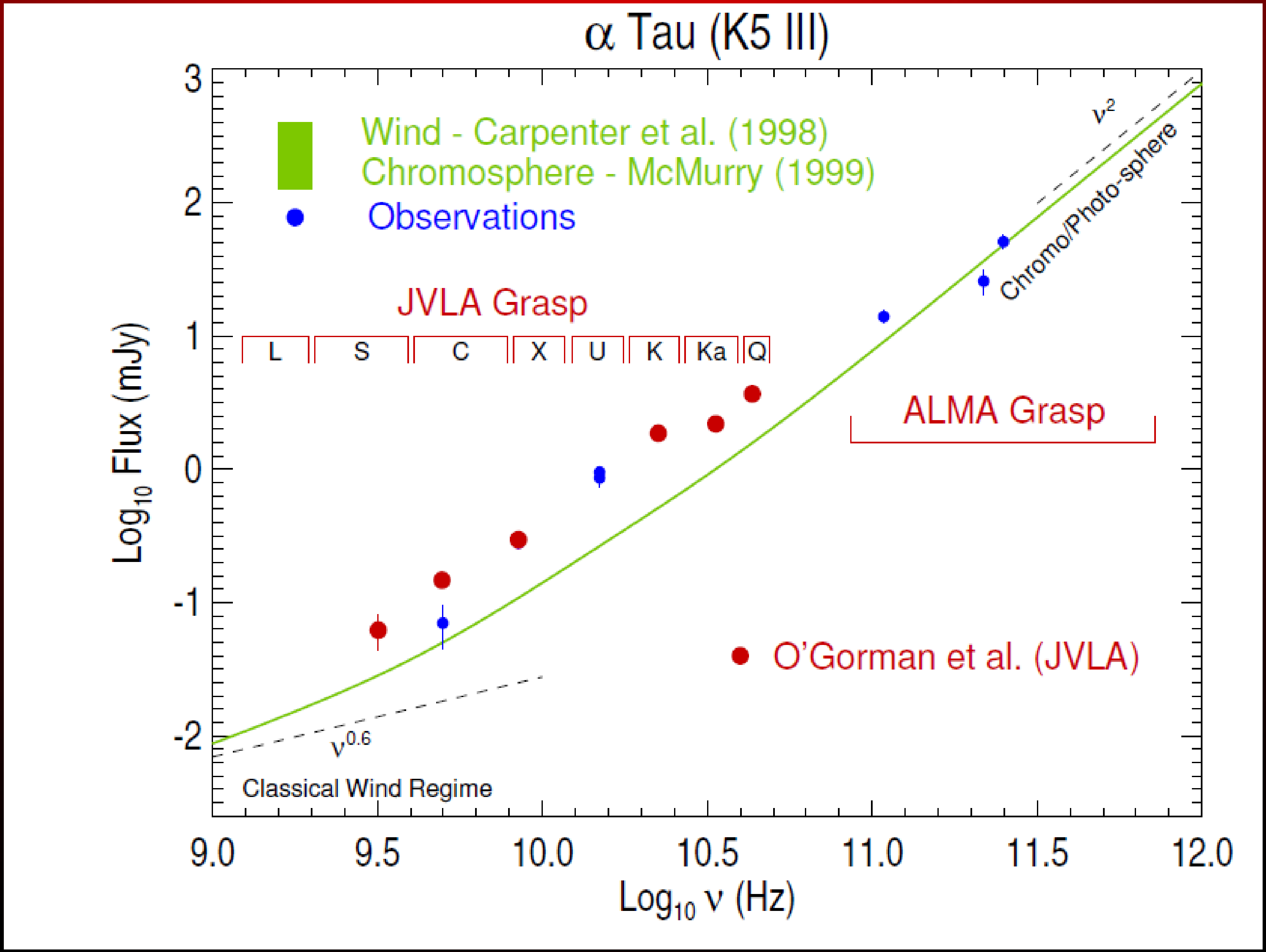
Contours = (-2,2,4,.....14)xσ
σ = 10 μJy

Contours = (-3,-2,-1,1,2,3)xσ
σ = 18 μJy

Spectral Energy Distribution *- α Tau*



Spectral Energy Distribution *- α Tau*

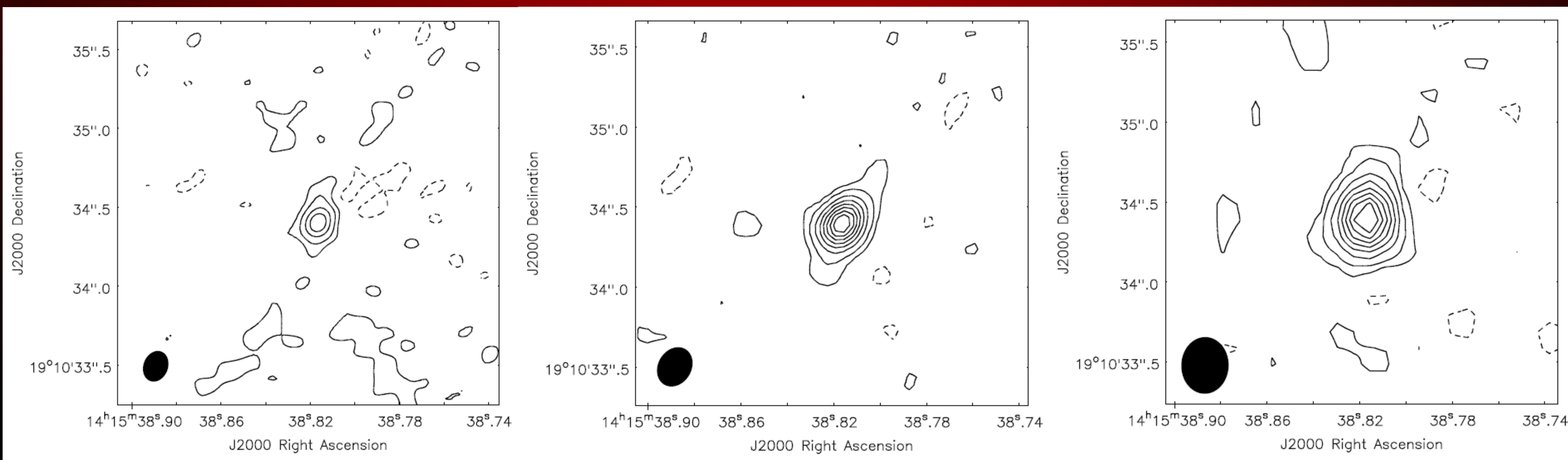


Results: α Boo – *High Frequencies*

Q-band (43 GHz)
S_v = 5.96 mJy

Ka-band (34 GHz)
S_v = 4.16 mJy

K-band (22 GHz)
S_v = 1.80 mJy



Contours = (-2,2,5,.....15)xσ
σ = 276 μJy

Contours = (-2,2,5,10,....35)xσ
σ = 100 μJy

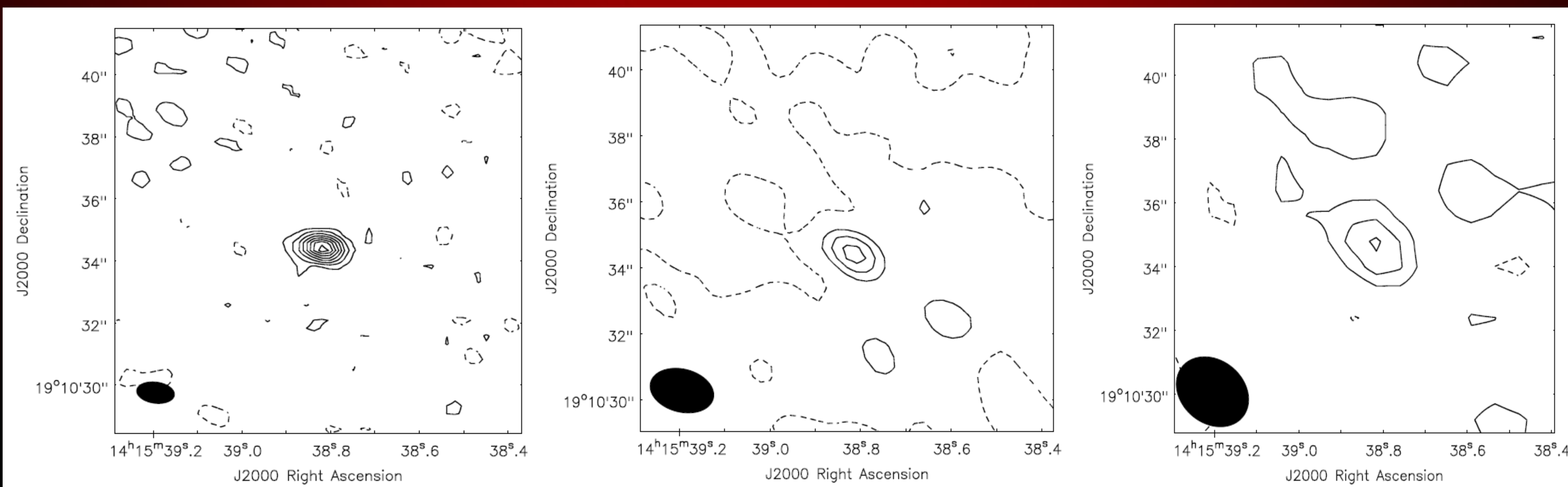
Contours = (-2,2,5,10,....35)xσ
σ = 40 μJy

Results: α Boo – *Low Frequencies*

X-band (8 GHz)
S_ν = 0.49 mJy

C-band (5 GHz)
S_ν = 0.18 mJy

S-band (3 GHz)
S_ν = 0.11 mJy



Contours = (-2,2,4......16)xσ
σ = 28 μJy

Contours = (-2,-1,1,2,3)xσ
σ = 52 μJy

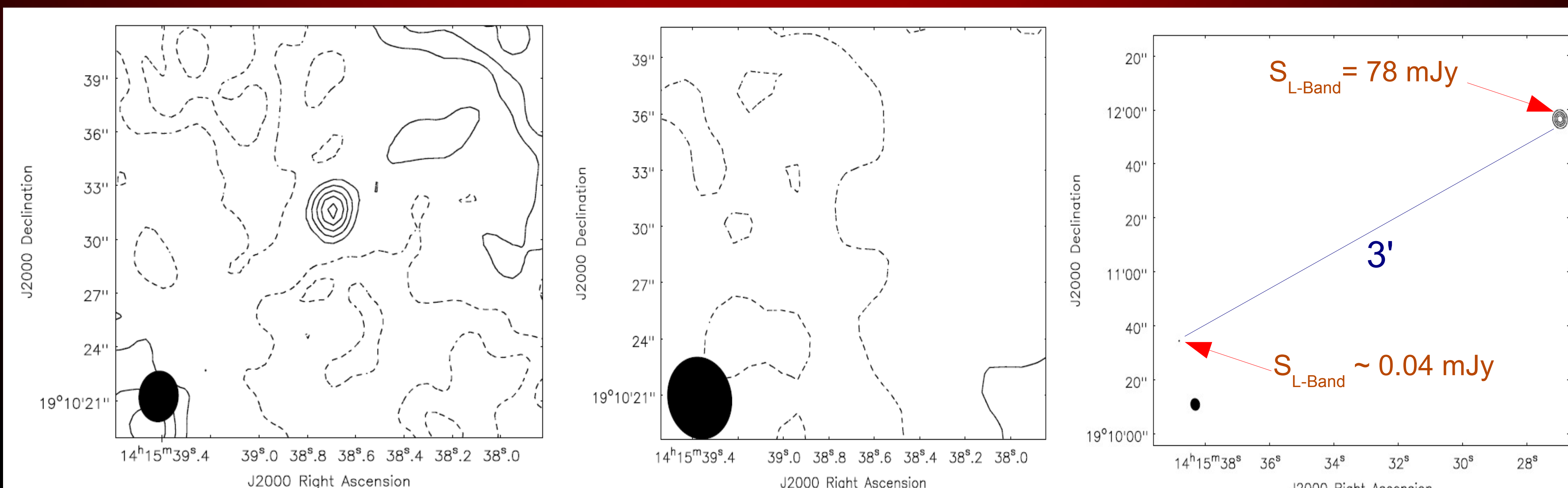
Contours = (-2-1,1,2,3)xσ
σ = 35 μJy

Results: α Boo – *Low Frequencies (DDT)*

S-band (2 - 4 GHz)
S_ν = 0.12 mJy

L-band (1-2 GHz)
S_ν = ? mJy

Strong 2nd Source @ L-band

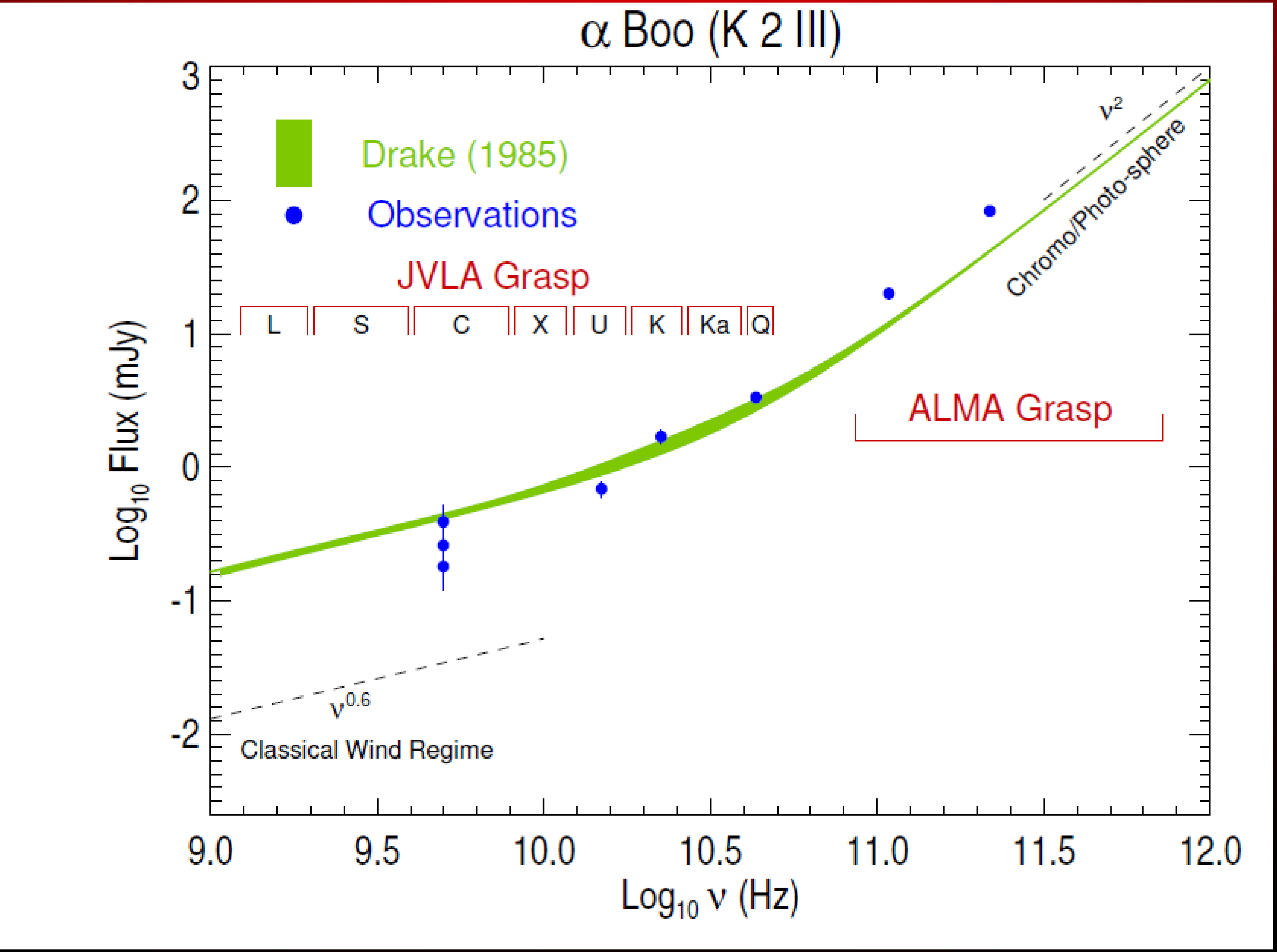


Contours = (-2,-1,1,2,3,4,5)xσ
σ = 22 μJy

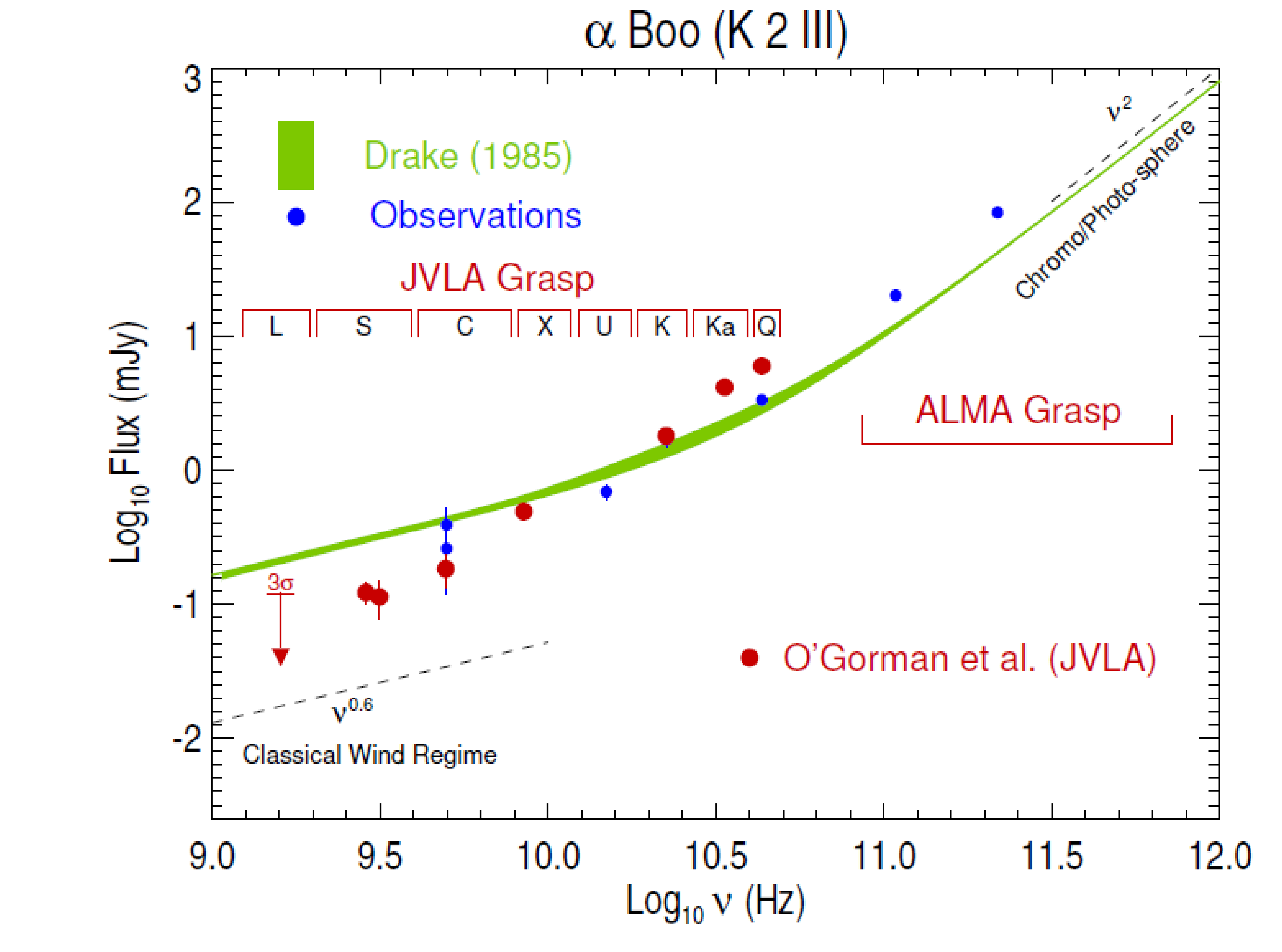
Contours = (-2,2,1,2,3)xσ
σ = 40 μJy

Dynamic Range Issue?

Spectral Energy Distribution - *α Boo*



Spectral Energy Distribution - *α Boo*



Hydrogen Ionization Code

Aim: Calculate the radio flux between 1 to 50 GHz for a grid of wind models, with different wind accelerations, mass-loss rates, and temperature profiles and see which model best fits our JVLA data.

Computes the hydrogen ionization as a function of R(z) using a 6-level model for H I (n=1 - 5 and n_K) using escape probabilities.

$$\cancel{\frac{\partial n_i}{\partial t}} + \nabla.(n_i V) = \sum_{i \neq j}^{n} n_j P_{ji} - n_i \sum_{j \neq 1}^{n} P_{ij}$$

Assume steady flow

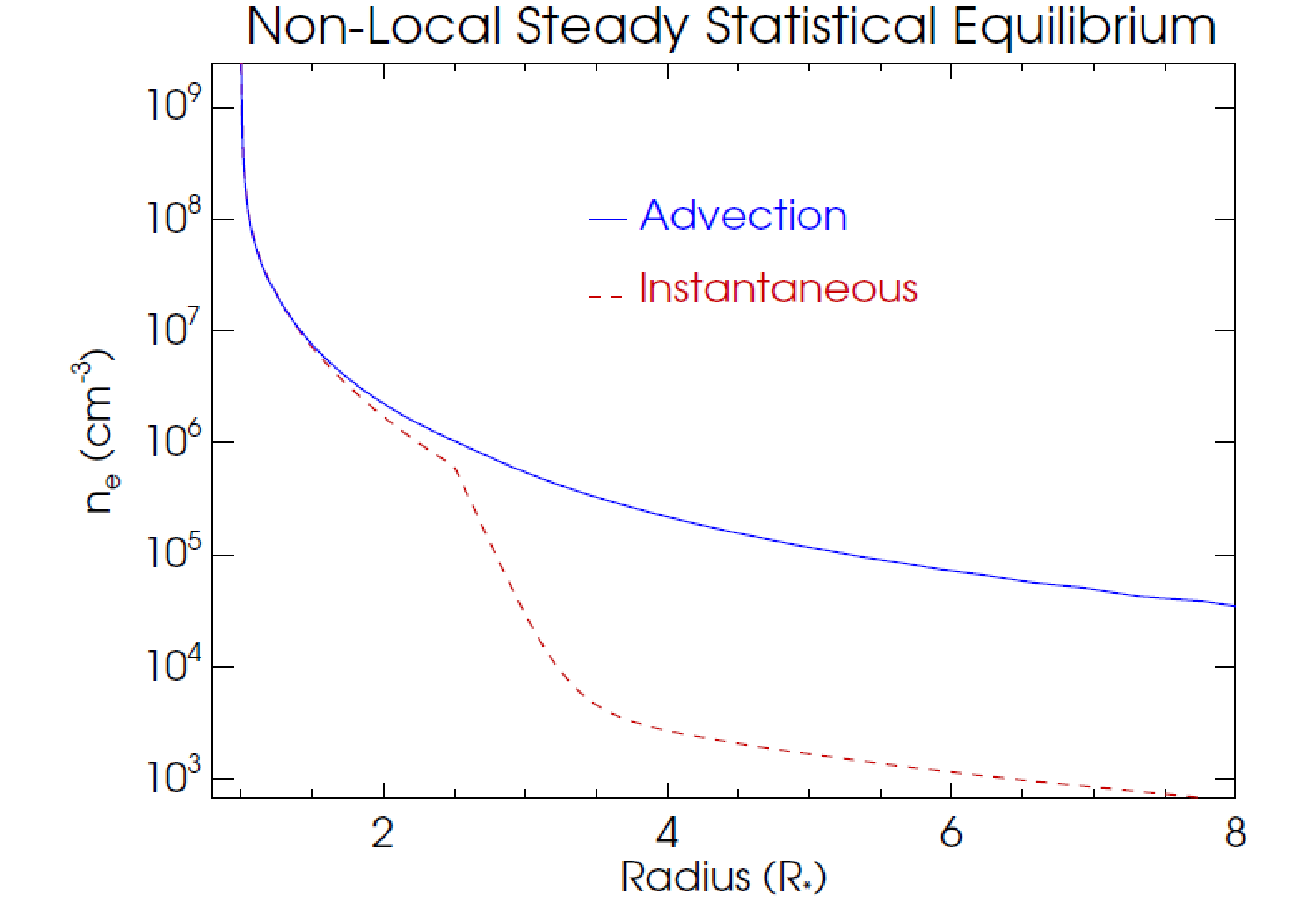
Statistical Equilibrium

Advection Term

Transition Probabilities

Hydrogen Ionization Code

Ionization state gets frozen into wind – *freezing-in of ionization balance*



Ionization state for in a stellar wind without/with advection

Conclusions & Future Work

1) Multi-frequency (S,C,X,K,Ka & Q-band) detections of two 'standard' red giants obtained over 11 days.

a) Improvements to radio maps at C (1 spw) and L-band for α Boo?

b) Use our hydrogen ionization code to match our JVLA fluxes and develop an accurate thermal and density outflow model for both stars.

c) Perform a comprehensive study into the thermal energy balance -> provide clues to the wind driving mechanism(s) (e.g. O'Gorman and Harper, 2011).

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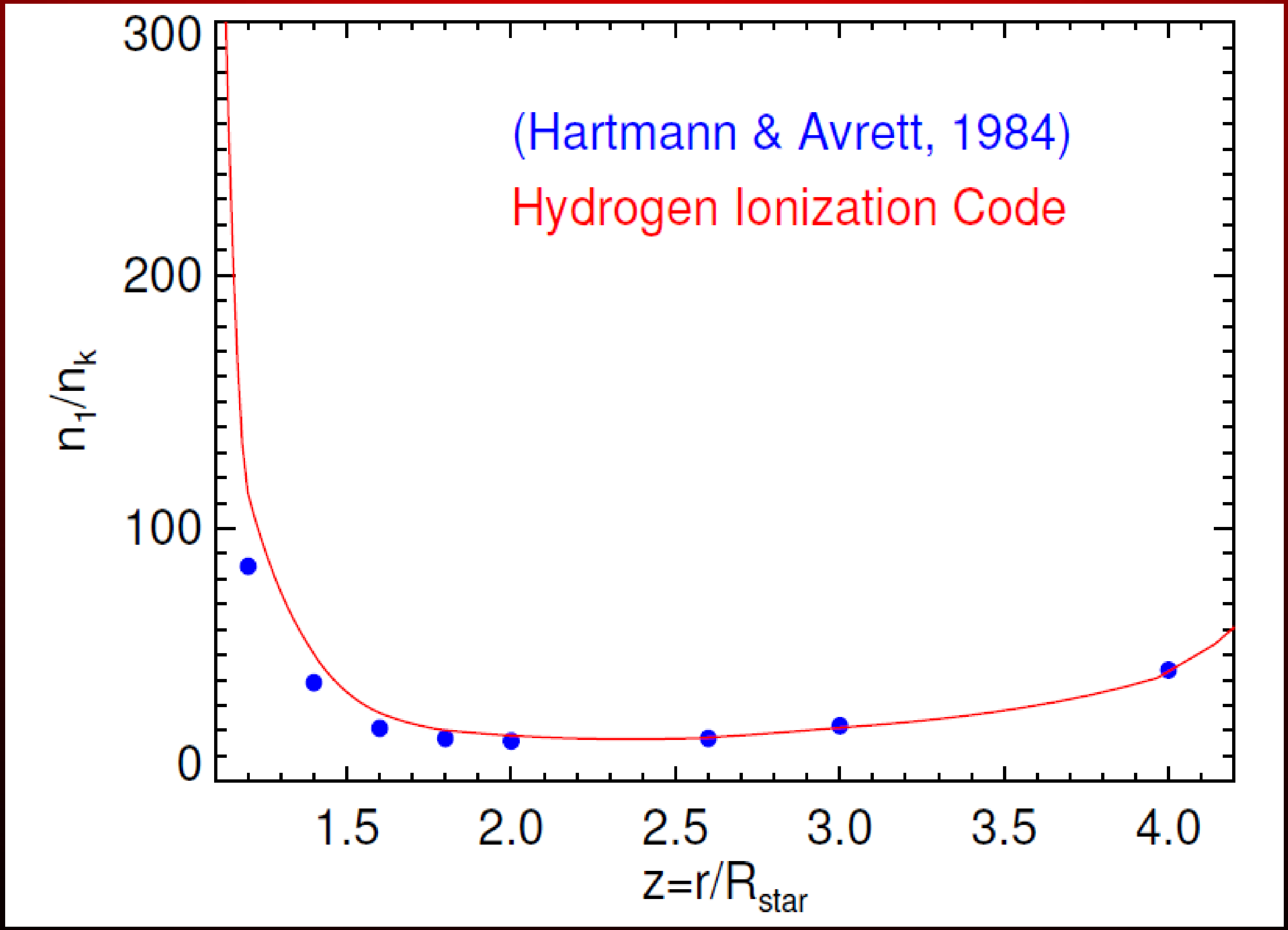
Thank you

Hydrogen Ionization Code



Test Case: α Ori