science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

NRF National Research Foundation | HartRAO Hartebeesthoek Radio Astronomy Observatory

SPECTROSCOPY
"the study of squiggly lines"

BY
G. Macleod, HartRAO
&
S. Goedhart, SKA-SA

HartRAO
The heartbeat of astronomy

SKA AFRICA
SQUARE KILOMETRE ARRAY

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

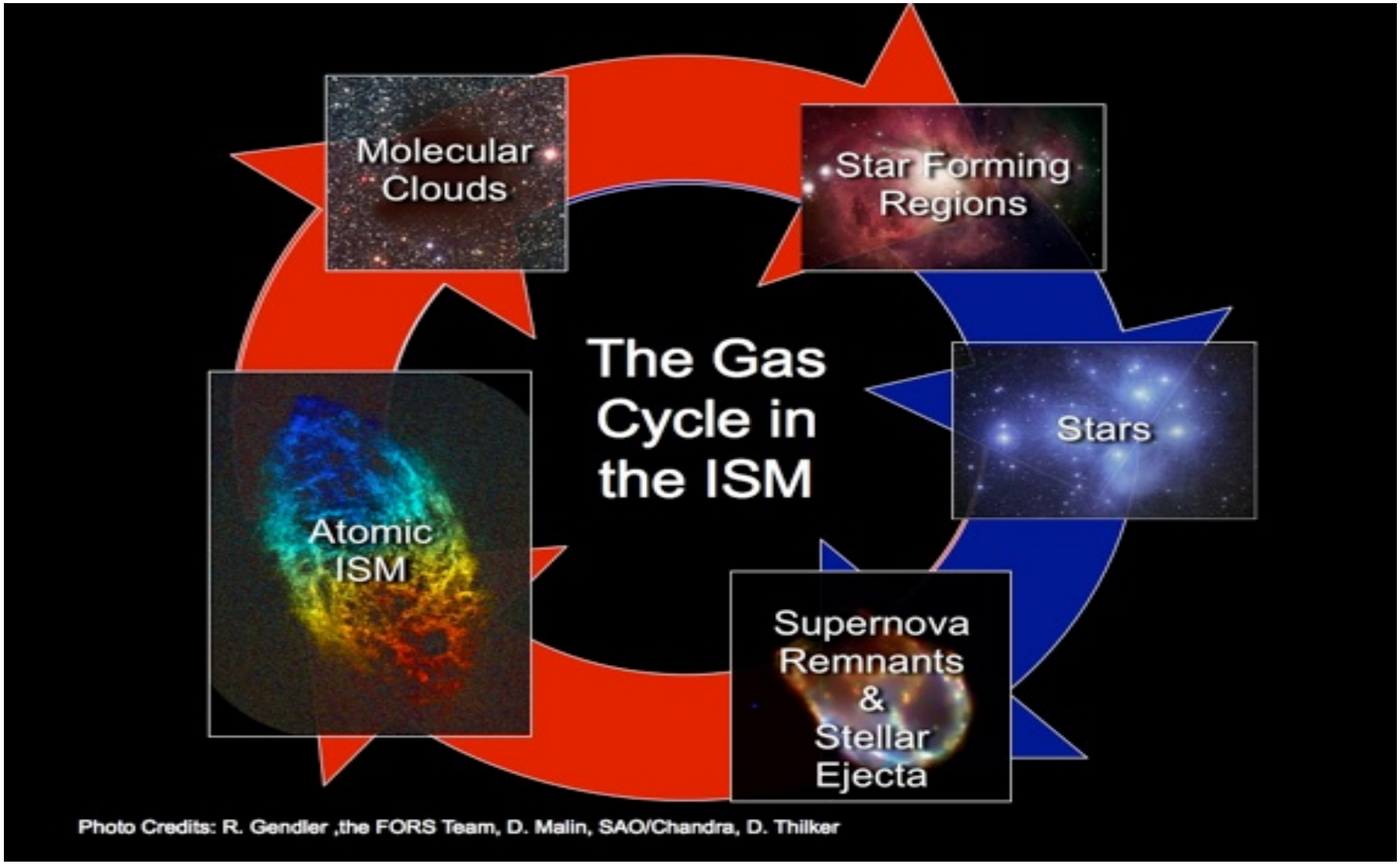
NRF
National Research Foundation
HartRAO
Hartebeesthoek Radio Astronomy Observatory

The Odd Sex Life of Molecular Clouds

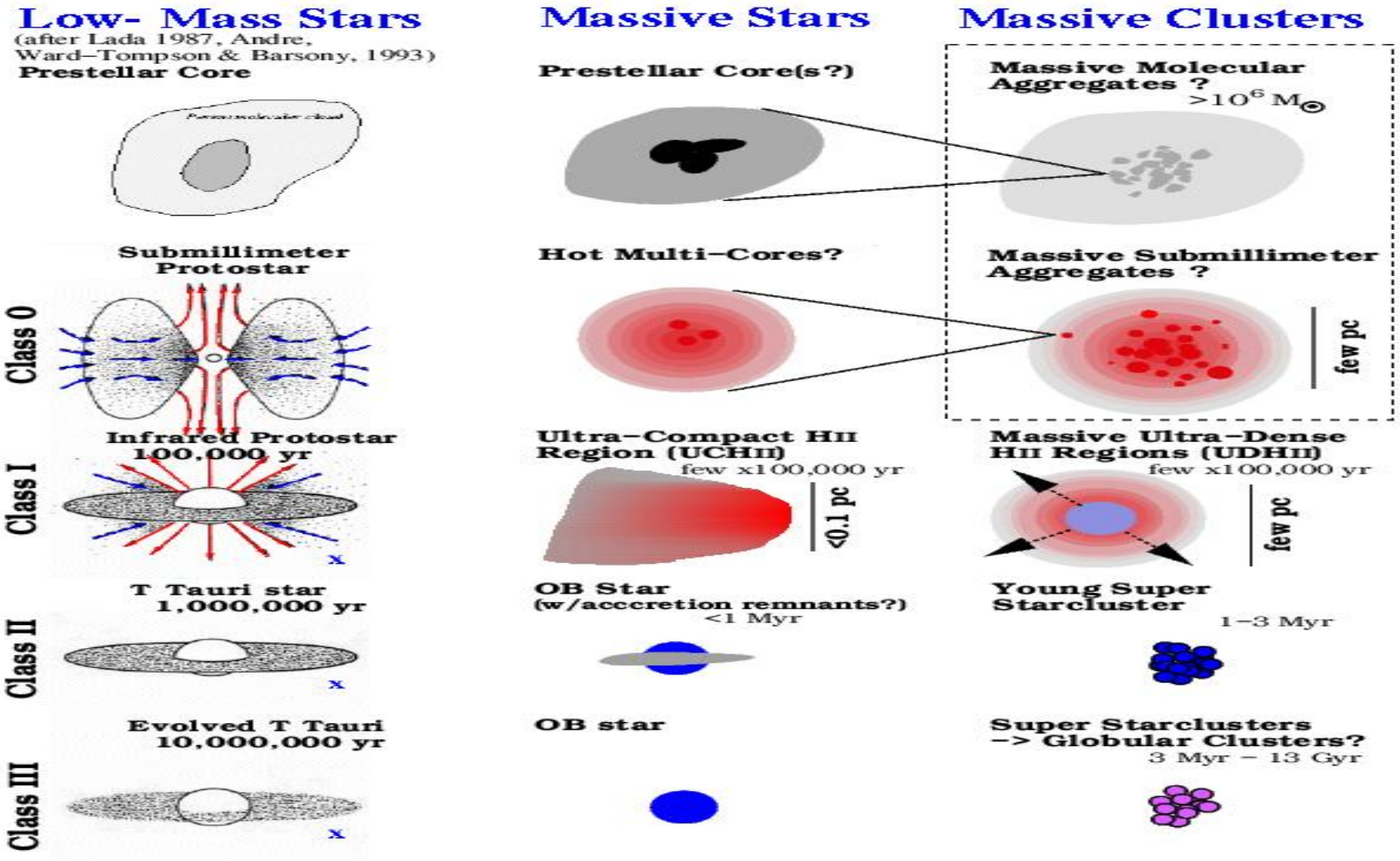
HartRAO
The heartbeat of astronomy

SKA AFRICA
SQUARE KILOMETRE ARRAY

Lifestyles of the Rich and Gaseous



LMCs' Children…



science & technology

Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

NRF
National Research Foundation

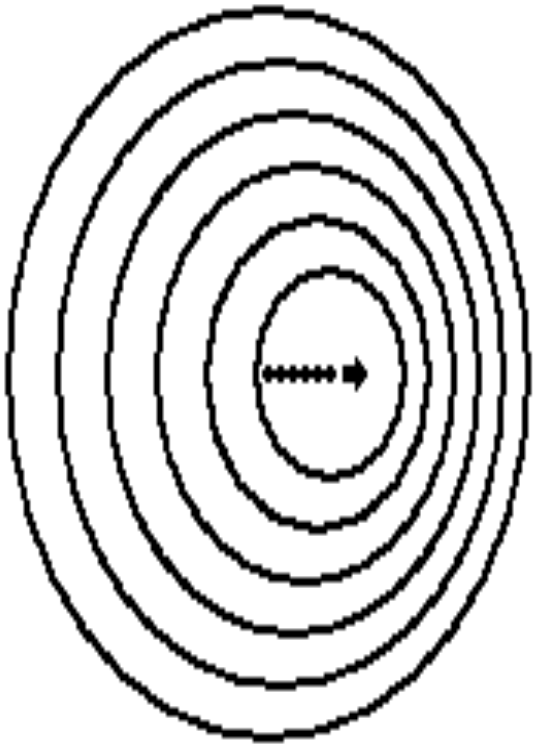
HartRAO
Hartebeesthoek Radio Astronomy Observatory

The Theory of Squiggly Lines

HartRAO
The heartbeat of astronomy

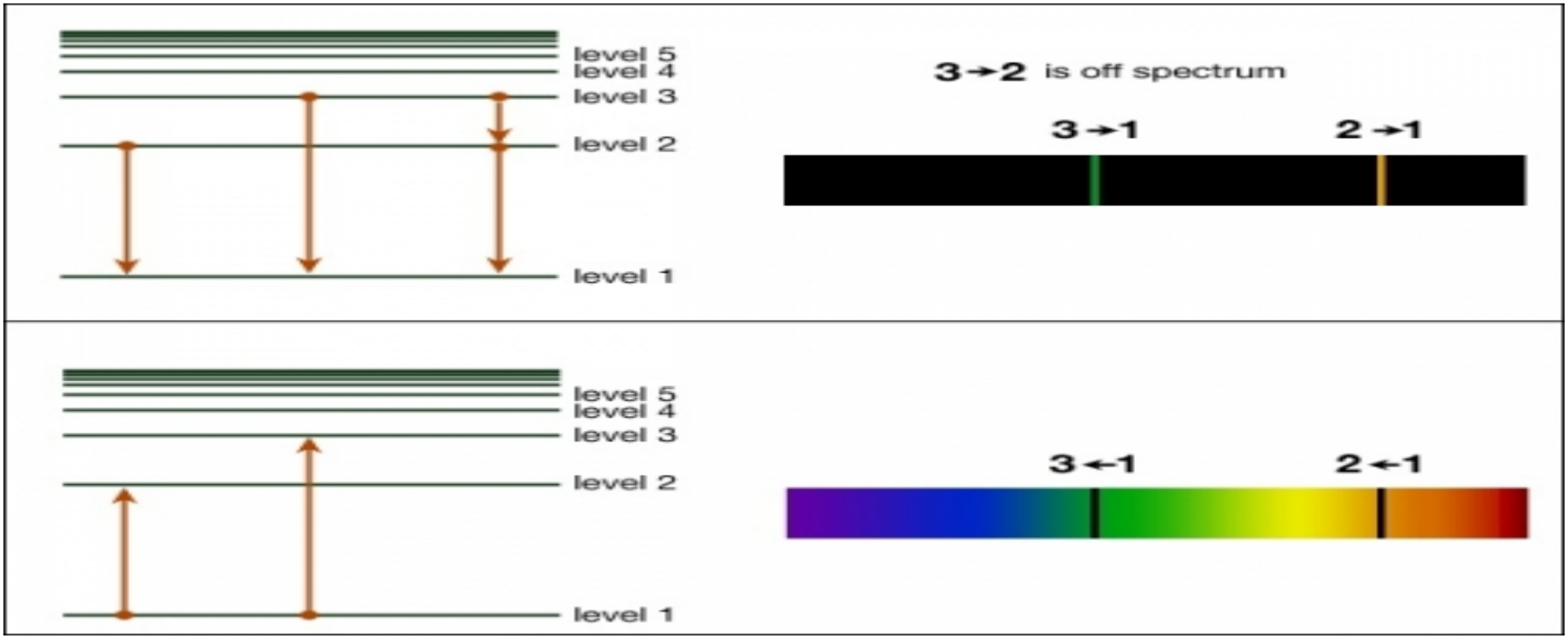
SKA AFRICA
SQUARE KILOMETRE ARRAY

OBJECT RECEDING:
LONG RED WAVES



OBJECT APPROACHING:
SHORT BLUE WAVES

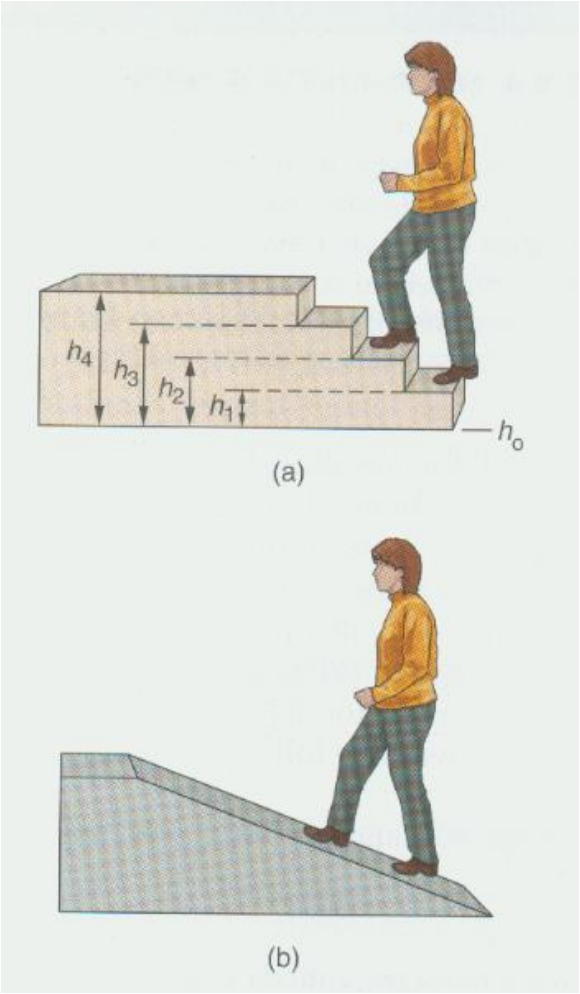
$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = \frac{\Delta\lambda}{\lambda_e} = \frac{v}{c}$$


level 5
level 4
level 3
level 2
level 1
3→2 is off spectrum
3→1
2→1
level 5
level 4
level 3
level 2
level 1
3←1
2←1

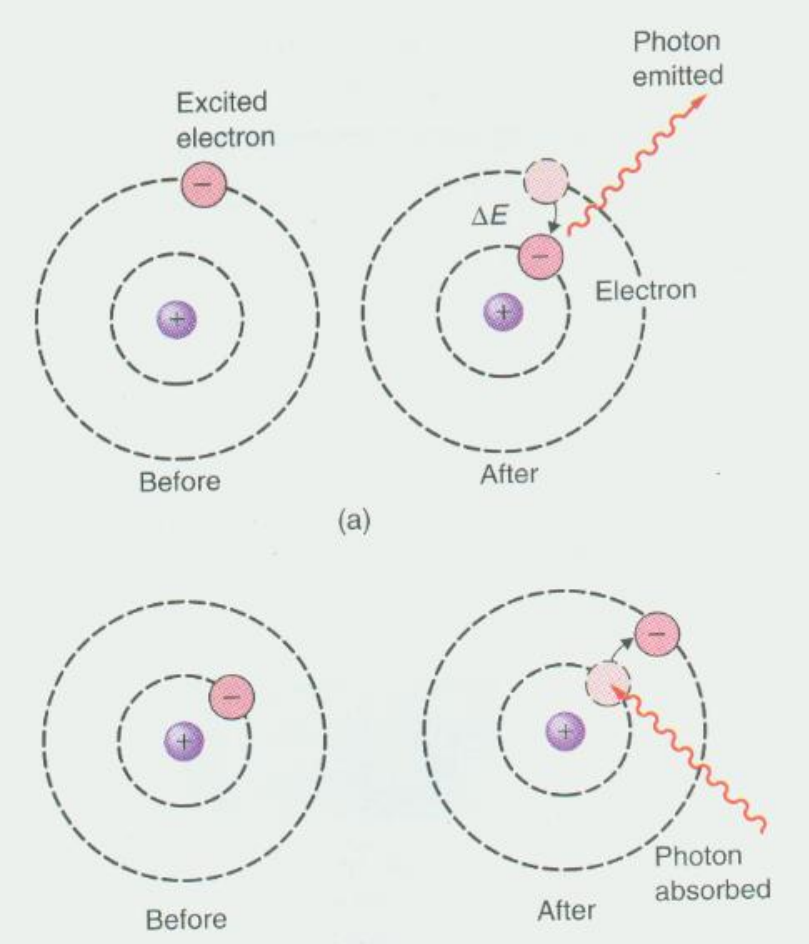

UNSHIFTED
REDSHIFTED
BLUESHIFTED

Quantized Energy

- Continuous energy is like a ramp.
- Quantized energy is like a stair case.
- Each stair increases the energy by the value of Planck's constant
- $h = 6.63 \times 10^{-34}$ J-s
- $E = hf$

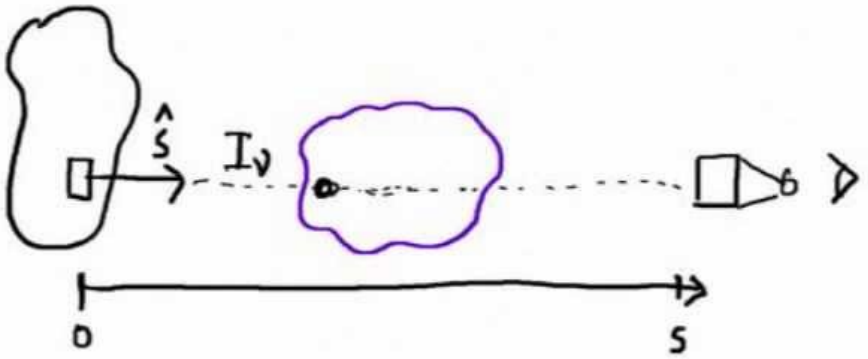


Absorption & Emission Spectra



- Bohr's model also explained Kirchhoff's Laws of Spectroscopy.
- Emission spectra produced when electron releases energy and drops to a lower orbit.
- Absorption spectra produced when electron absorbed energy needed to go to a higher orbit.

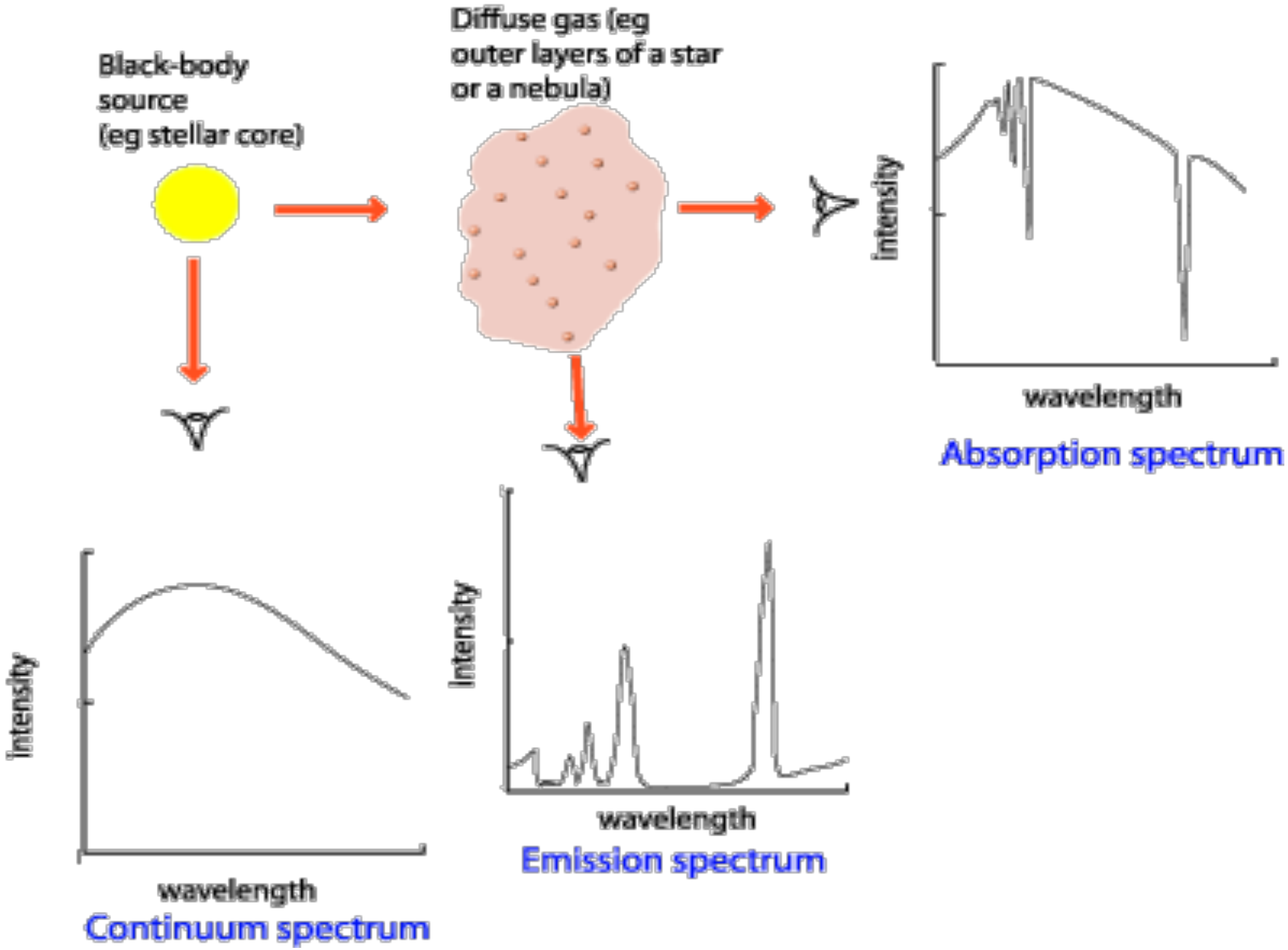
Radiative Transport Equation



$$\frac{dI_\nu}{ds} = \underbrace{j_\nu}_{\text{emission}} - \underbrace{\alpha_\nu I_\nu}_{\text{absorption scattering}}$$

$$I_\nu(\tau_\nu) = \underbrace{I_{\nu 0}\, e^{-\tau_\nu}}_{} + \int_0^{\tau_\nu} S_\nu(\tau_\nu')\, \underbrace{e^{-(\tau_\nu - \tau_\nu')}}_{\text{self absorption}}\, d\tau_\nu'$$

$$\frac{dI_\nu}{d\tau_\nu} = \underbrace{\frac{j_\nu}{\alpha_\nu}}_{\text{source function} \equiv S_\nu} - I_\nu$$


Black-body source (eg stellar core)
Diffuse gas (eg outer layers of a star or a nebula)
intensity
wavelength
Absorption spectrum
intensity
wavelength
Emission spectrum
intensity
wavelength
Continuum spectrum

The Real Math…

3-level system

$$n_1(B_{12}J_\nu + C_{12} + B_{13}J_\nu + C_{13}) = n_2(A_{21} + B_{21}J_\nu + C_{21}) + n_3(A_{31} + B_{31}J_\nu + C_{31})$$
$$n_2(A_{21} + B_{21}J_\nu + C_{21} + B_{23}J_\nu + C_{23}) = n_1(B_{12}J_\nu + C_{12}) + n_3(A_{32} + B_{32}J_\nu + C_{32})$$

$$\frac{n_i}{n_j} = \frac{g_i}{g_j}\,\mathrm{e}^{-\frac{h\nu}{kT_{ij}}} \;; \qquad T_{ij} = \text{excitation temperature}$$

$$\frac{C_{ji}}{C_{ij}} = \frac{g_i}{g_j}\,\mathrm{e}^{-\frac{h\nu}{kT_{\mathrm{K}}}} \;; \qquad T_{\mathrm{K}} = \text{kinetic temperature}$$

$$C_{ij} = n_{\mathrm{H_2}}\langle v\,\sigma_{ij}\rangle$$

$$J_\nu = S_\nu(1 - \mathrm{e}^{-\tau_{ij}}) + B_\nu(T_{\mathrm{R}})\,\mathrm{e}^{-\tau_{ij}} \;; \qquad T_{\mathrm{R}} = \text{radiation temperature}$$

$$S_\nu \equiv \frac{j_\nu}{\kappa} = \frac{n_i A_{ij}}{n_j B_{ji} - n_i B_{ij}} = B_\nu(T_{ij})$$

$$\tau_{ij} = \frac{h\nu}{4\pi\Delta\nu} B_{ij}\, X\, N_{\mathrm{H_2}} \frac{\mathrm{e}^{\frac{h\nu}{kT_{ij}}} - 1}{\frac{g_j}{g_i}\,\mathrm{e}^{\frac{h\nu}{kT_{ij}}} + 1} \;; \qquad X \equiv \text{abundance relative to } \mathrm{H_2}$$

Radiative transfer equation: the line case

Simple case of *uniform*, *homogeneous* cloud:

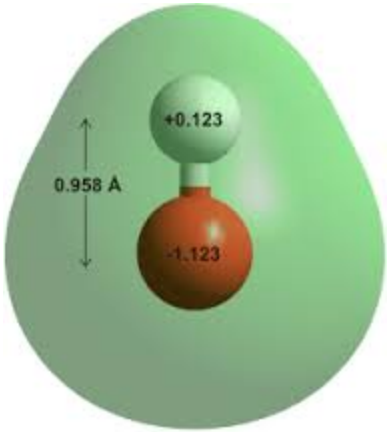
$$I_\nu = (B_\nu(T_{\rm ex}) - B_\nu(T_{\rm BG}))\left(1 - {\rm e}^{-\tau}\right)$$

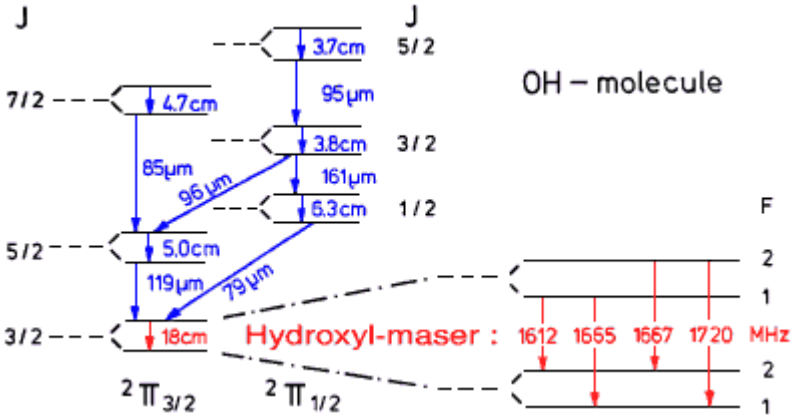
With the additional definition of **brightness temperature**, $I_\nu \equiv B_\nu(T_{\rm B})$, and under the Rayleigh-Jeans approximation, $h\nu \ll kT_{\rm ex}$ and $h\nu \ll kT_{\rm B}$, one gets:

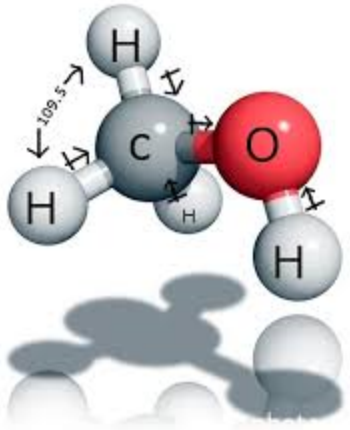
$$T_{\rm B} = (T_{\rm ex} - T_{\rm BG})\left(1 - {\rm e}^{-\tau}\right)$$

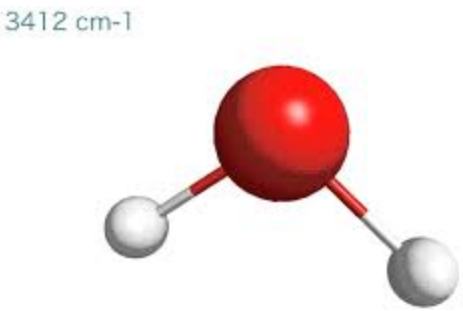
- $T_{\rm ex} > T_{\rm BG} \Rightarrow T_{\rm B} > 0$ emission line
- $0 < T_{\rm ex} < T_{\rm BG} \Rightarrow T_{\rm B} < 0$ absorption line
- $T_{\rm ex} < 0 \Rightarrow \tau < 0 \Rightarrow T_{\rm B} \gg T_{\rm BG}$ **maser** line: e.g. $T_{\rm B} \simeq 10^{10}$ K !!!

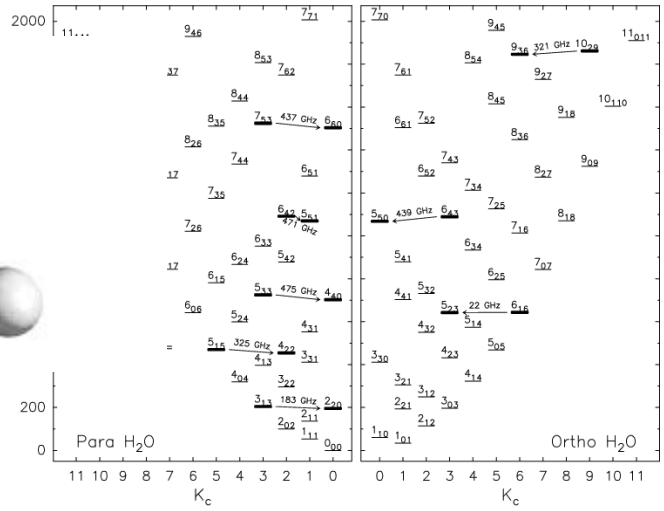
Different Molecules

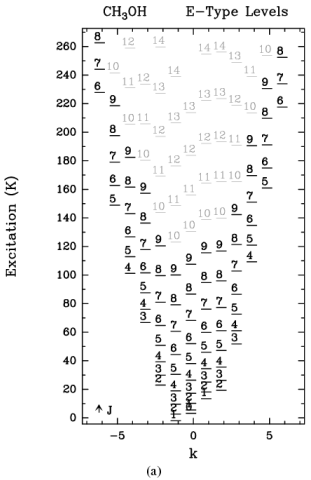


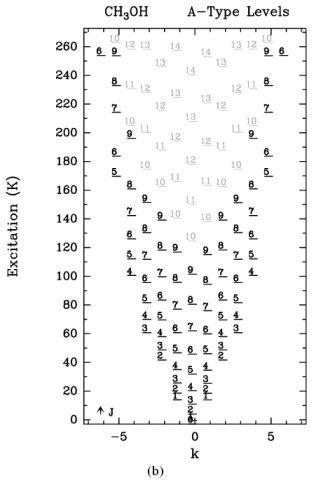


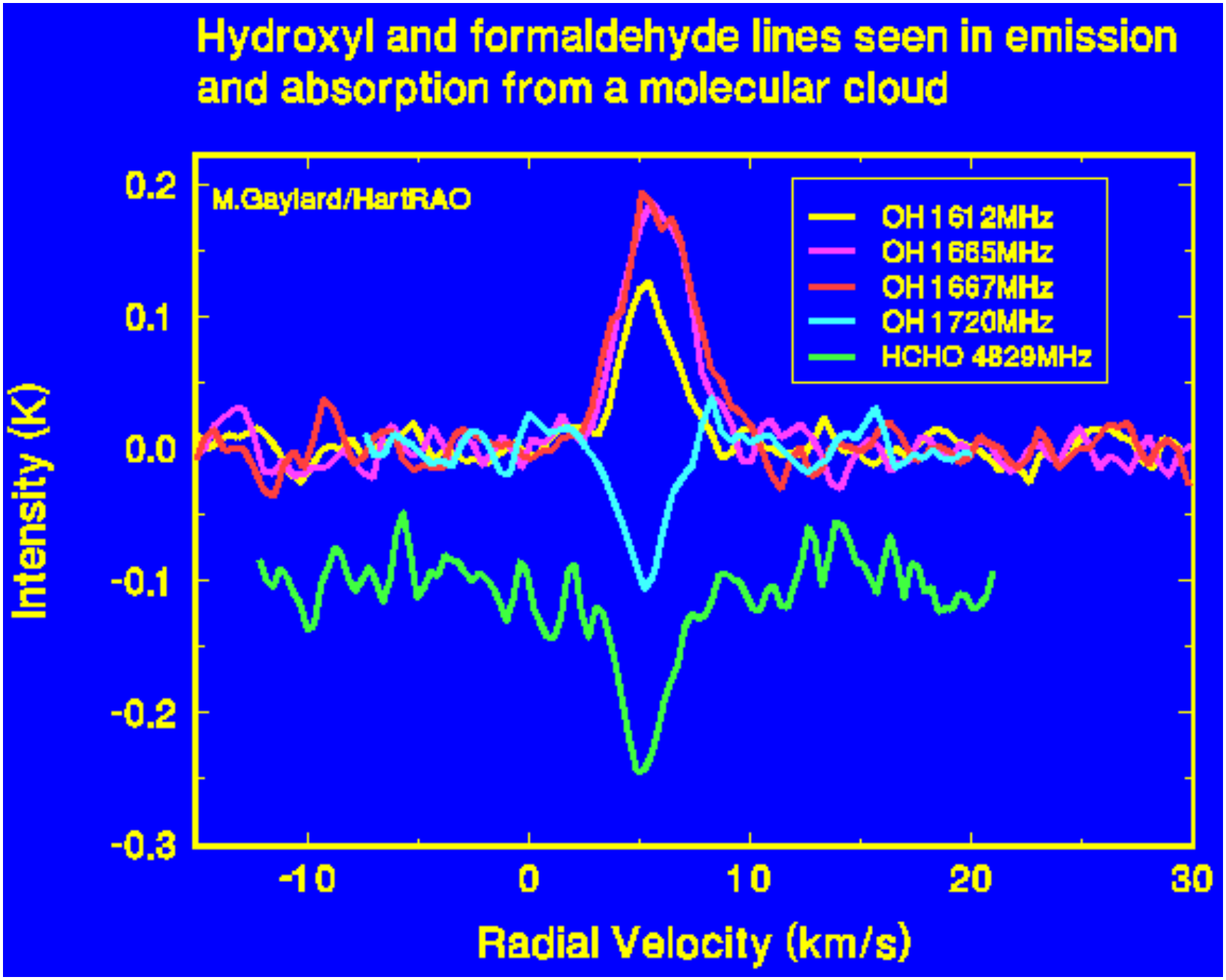


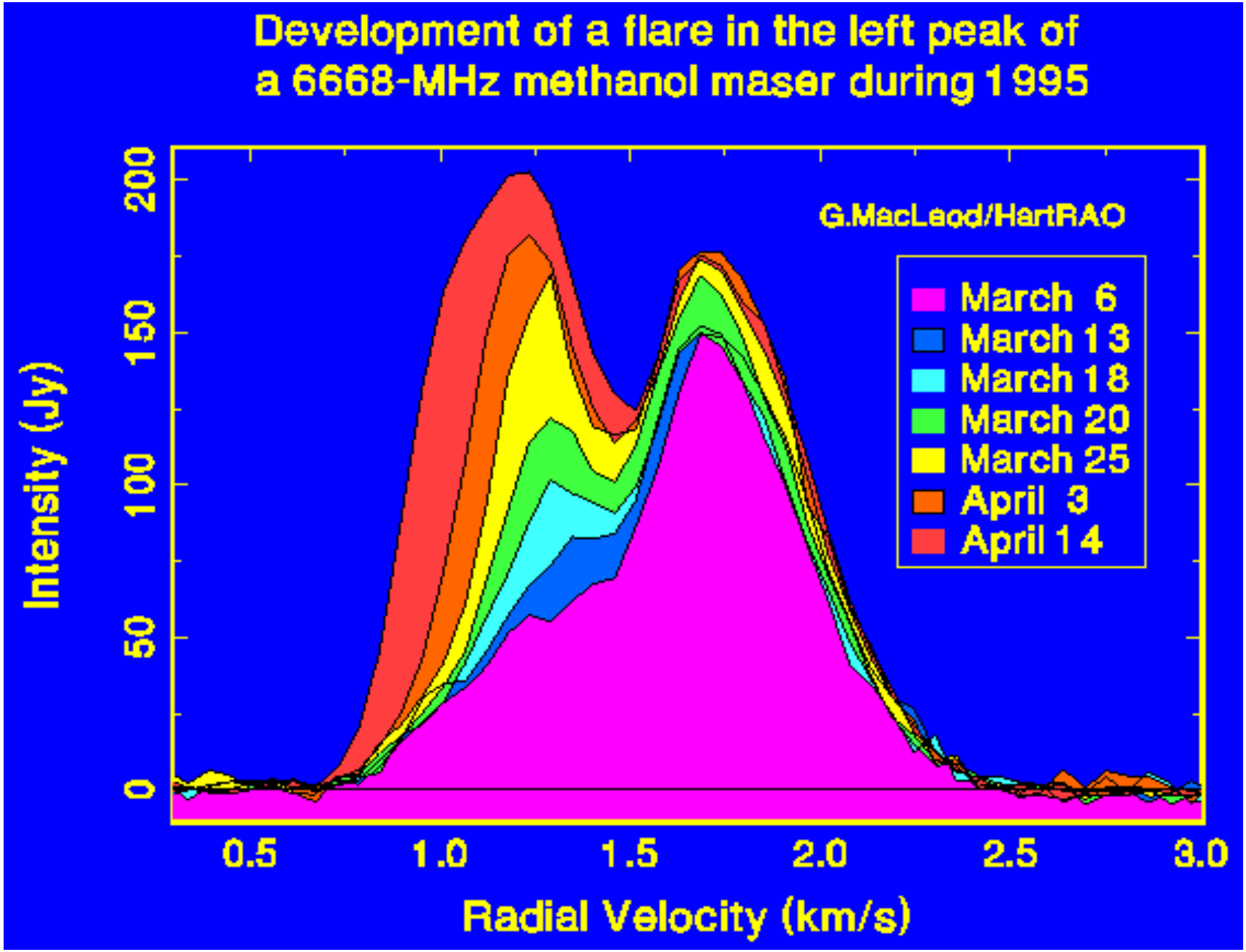


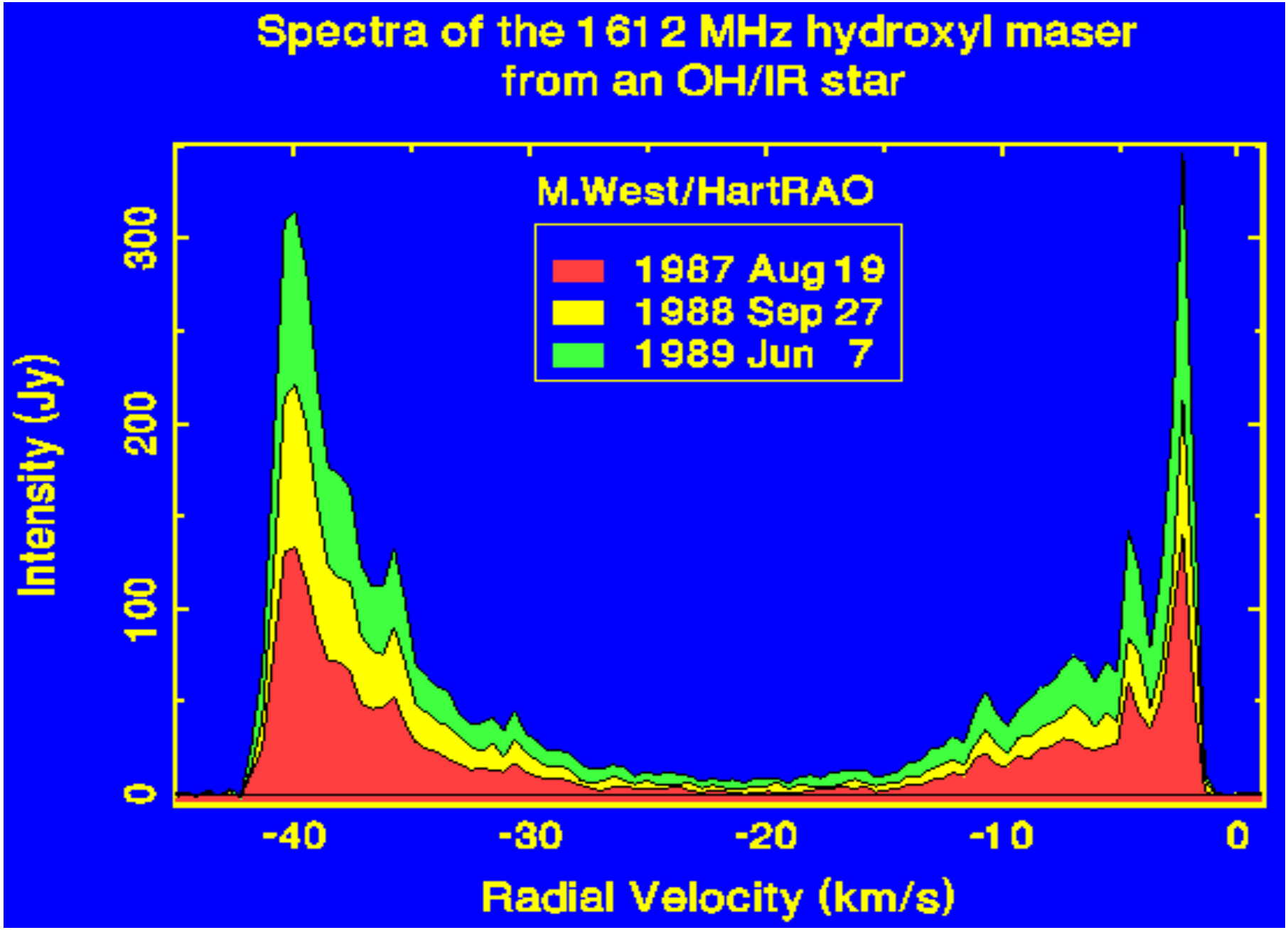


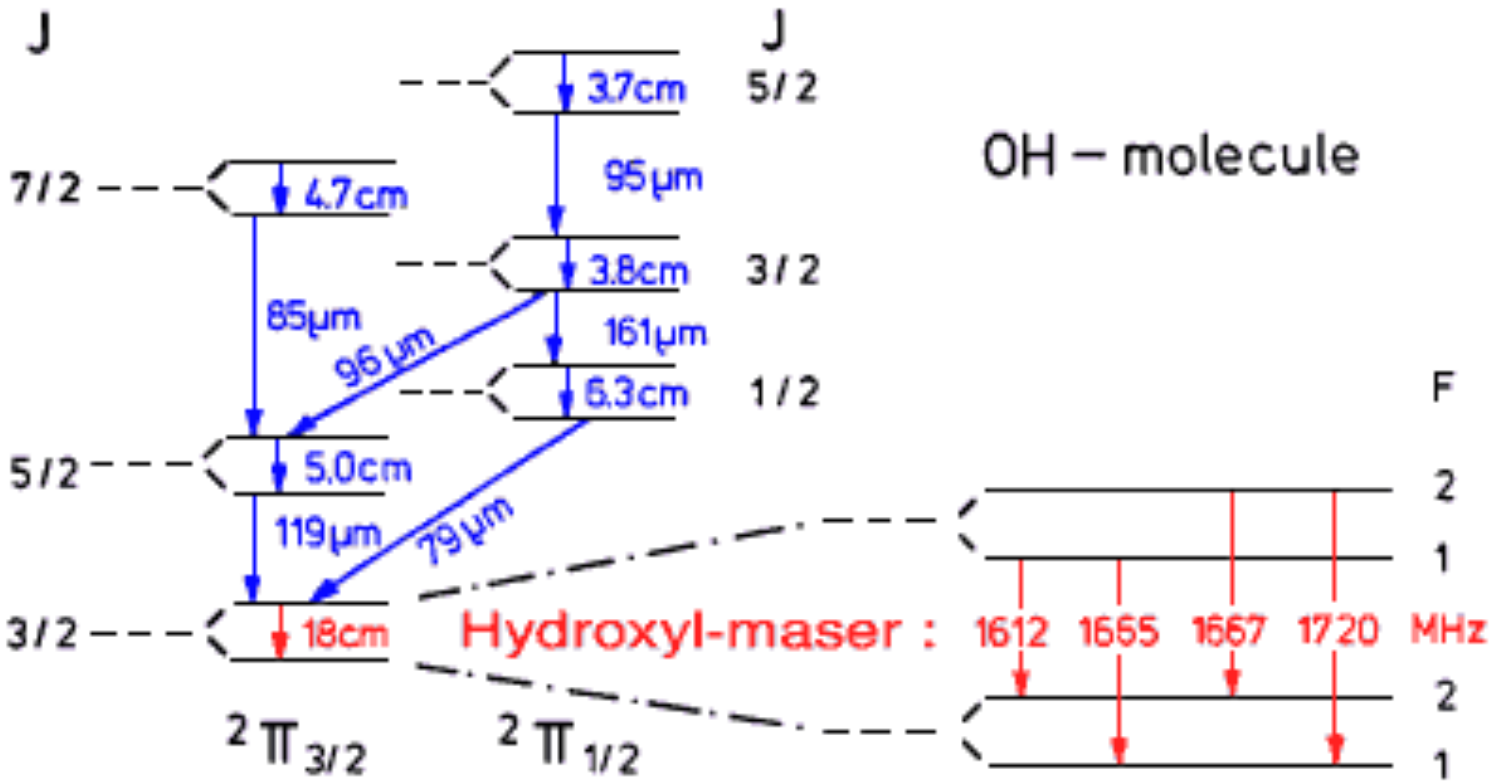




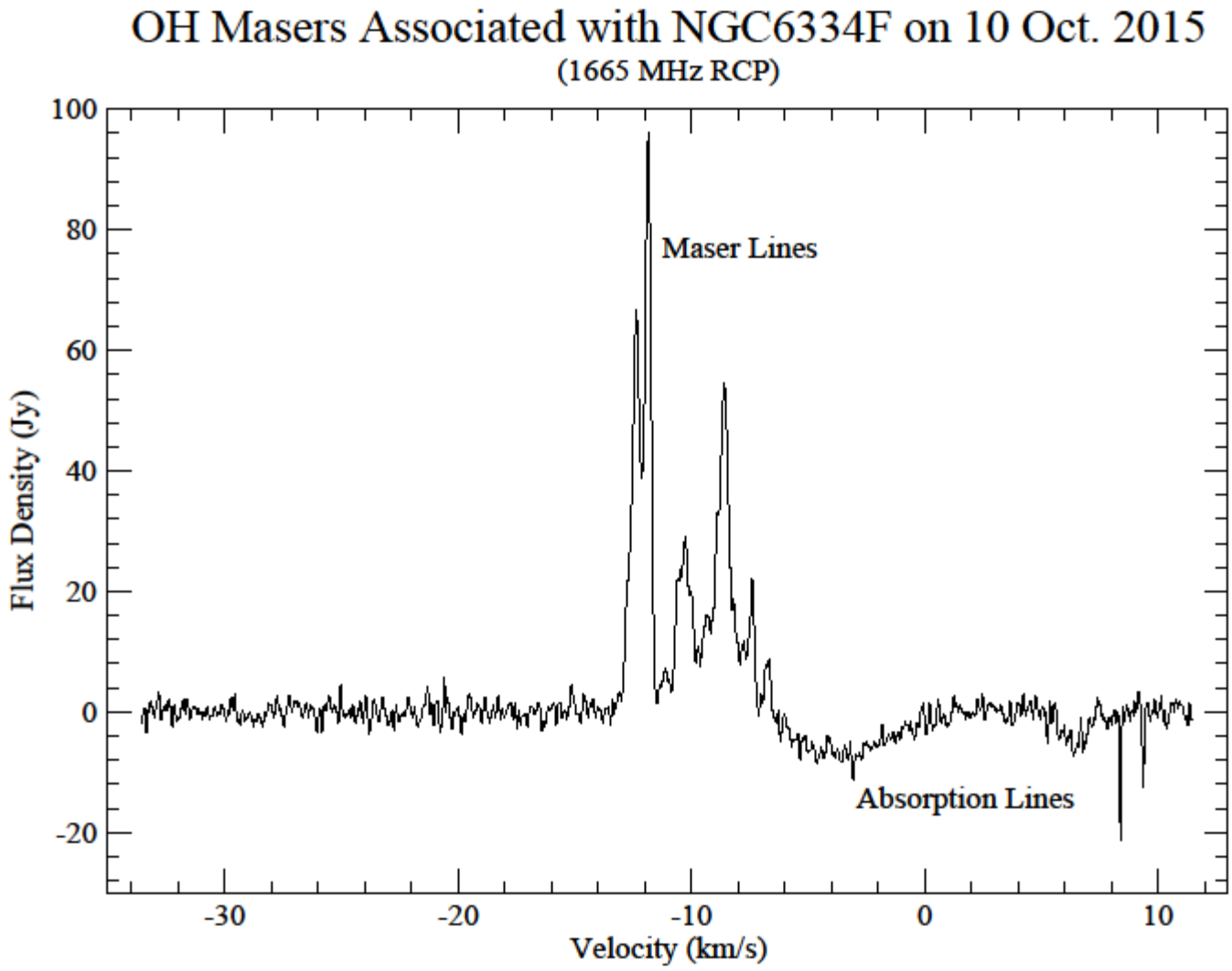

Hydroxyl and formaldehyde lines seen in emission and absorption from a molecular cloud
M.Gaylard/HartRAO
OH 1612MHz
OH 1665MHz
OH 1667MHz
OH 1720MHz
HCHO 4829MHz
0.2
0.1
0.0
-0.1
-0.2
-0.3
Intensity (K)
-10
0
10
20
30
Radial Velocity (km/s)


Development of a flare in the left peak of
a 6668-MHz methanol maser during 1995
G.MacLeod/HartRAO
March 6
March 13
March 18
March 20
March 25
April 3
April 14
Intensity (Jy)
0
50
100
150
200
0.5
1.0
1.5
2.0
2.5
3.0
Radial Velocity (km/s)


Spectra of the 1612 MHz hydroxyl maser
from an OH/IR star
M.West/HartRAO
1987 Aug 19
1988 Sep 27
1989 Jun 7
Intensity (Jy)
0
100
200
300
-40
-30
-20
-10
0
Radial Velocity (km/s)



$$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}$$

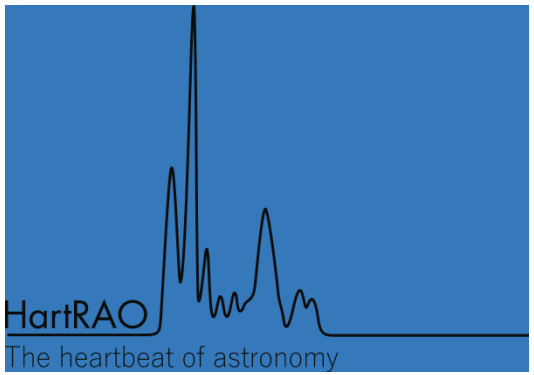

OH Masers Associated with NGC6334F on 10 Oct. 2015
(1665 MHz RCP)
Flux Density (Jy)
100
80
60
40
20
0
-20
Maser Lines
Absorption Lines
-30
-20
-10
0
10
Velocity (km/s)

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

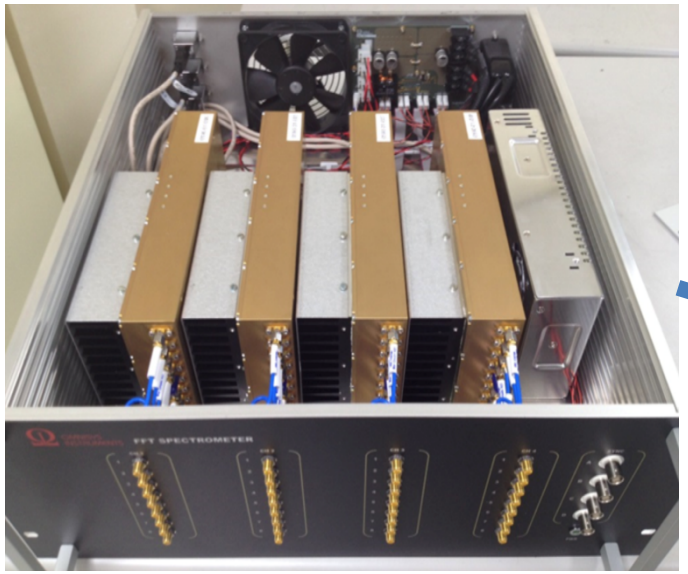
NRF
National Research Foundation

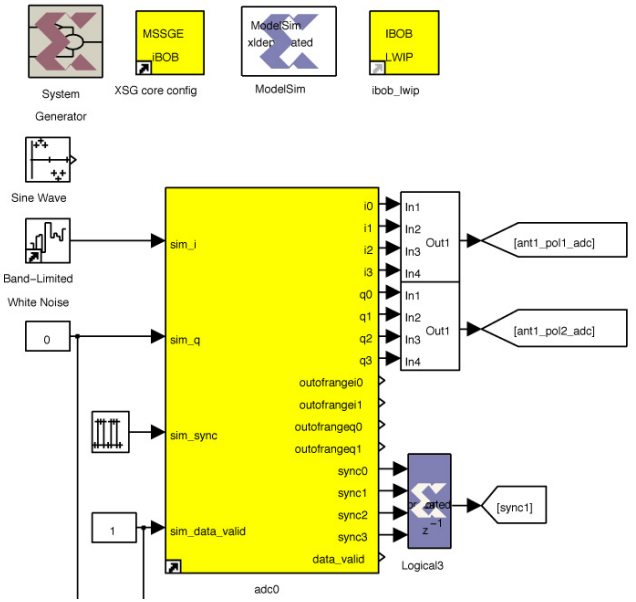
HartRAO
Hartebeesthoek Radio Astronomy Observatory

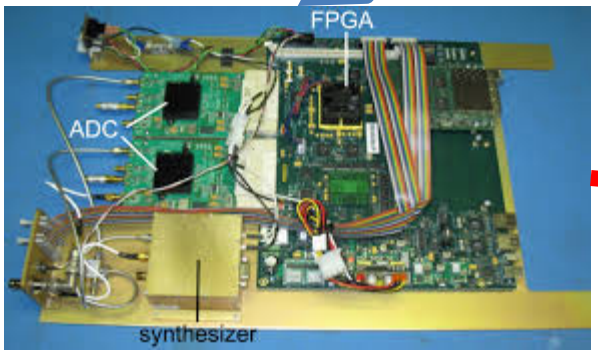
What's a Spectrometer?

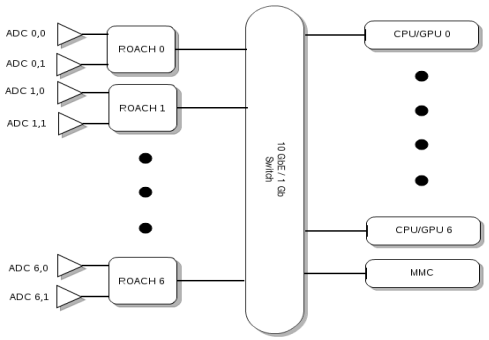


Hardware vs. Software









A Spectrometer

Filter Bank Spectrometer

Originally separate banks of filters each centered on slightly different IF

Split power coming into filterbank with N channels

Adjust velocity resolution by changing the bandwidth used in the observations.

- E.g. 100 MHz for N=100 channels -> 1 MHz resolution
- Convert to velocity using the Local standard of rest frequency and line velocity.

Square-law detectors

Recorder

Note

Signal to noise worse the more channels so require appropriate integration time.

Digital Spectrometer

More controllable

- Convert signal to digital asap
- Able to select velocity region in bandpass, regardless of width.
- Vary the number of channels

A lot more data

- Very short integration time on chip – can cause problems
- Must process spectra in CPU off chip
- Can do all stokes parameters simultaneously

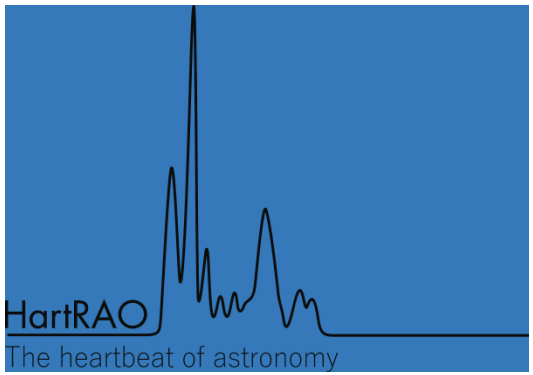
science & technology

Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

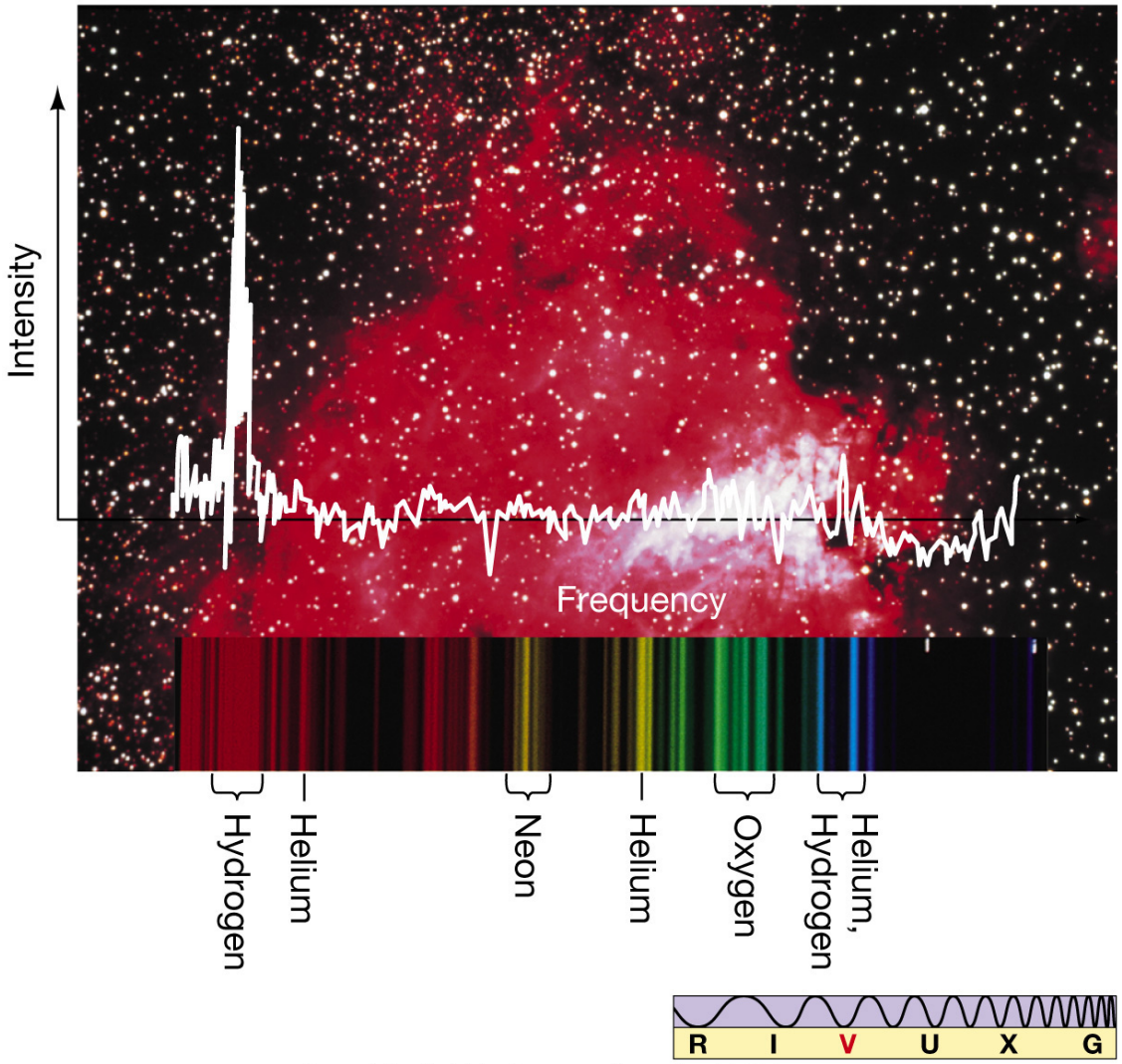
National Research Foundation

HartRAO
Hartebeesthoek Radio Astronomy Observatory

Clouds and the ISM



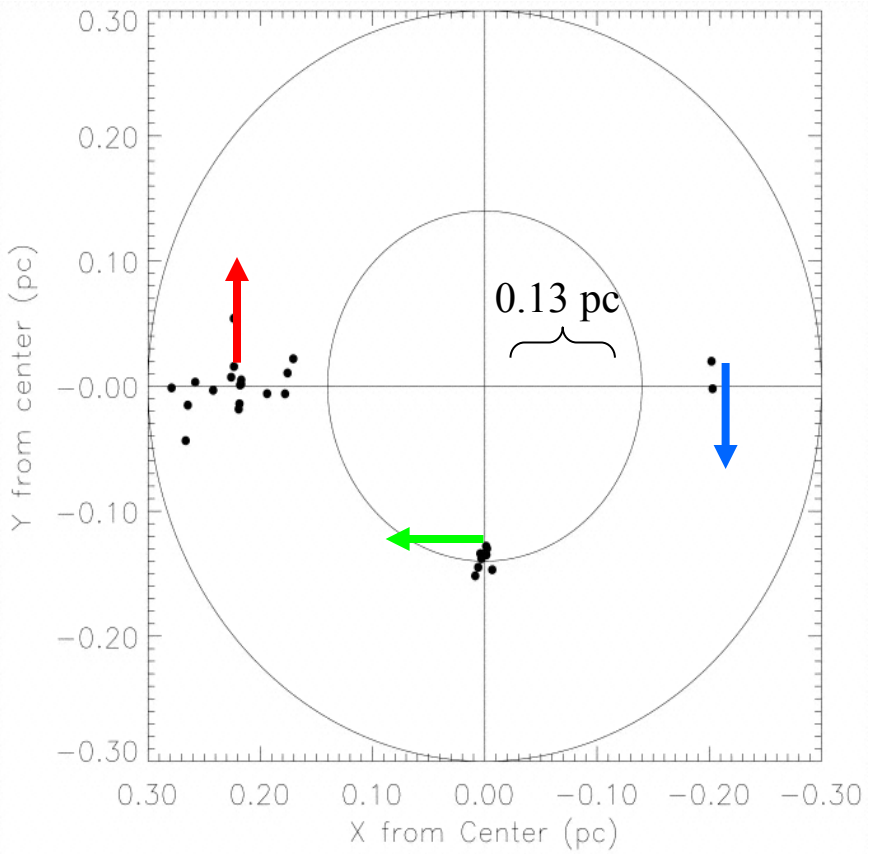
Emission lines can be used to identify atoms:



Copyright © 2005 Pearson Prentice Hall, Inc.

H_2O masers in galaxy NGC4258

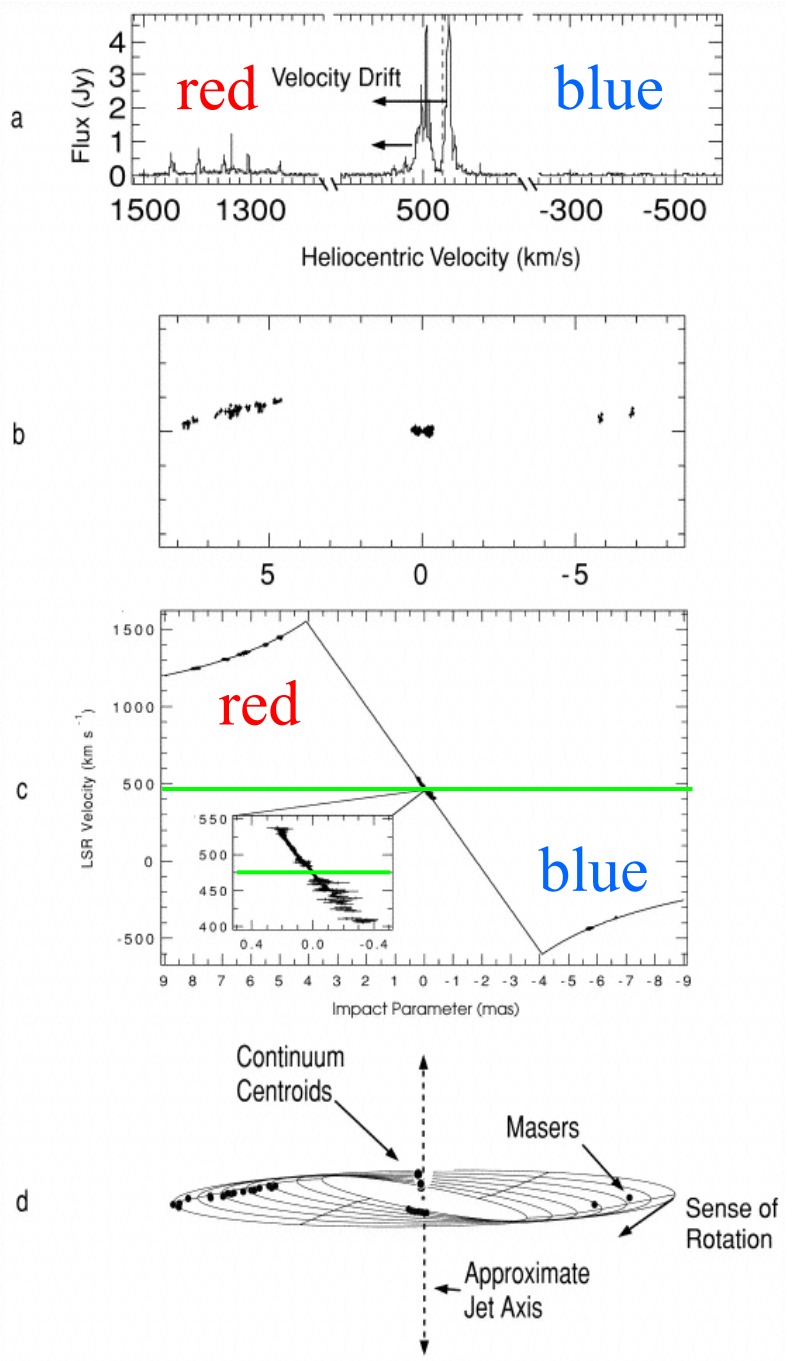
Miyoshi et al. (1995)



central mass from Keplerian law:

$M = V^2R/G = 3.6\ 10^7\ M_O$ } **black hole!**

density $> 4\ 10^9\ M_O\ pc^{-3}$ }



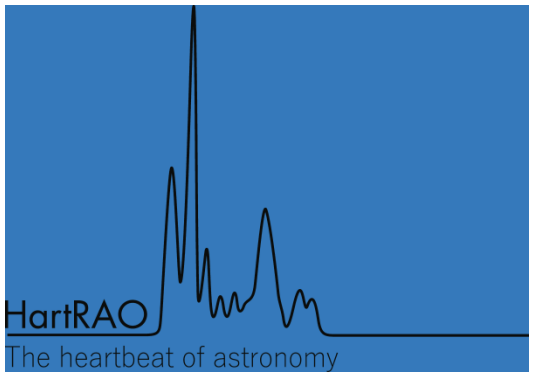
science & technology

Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

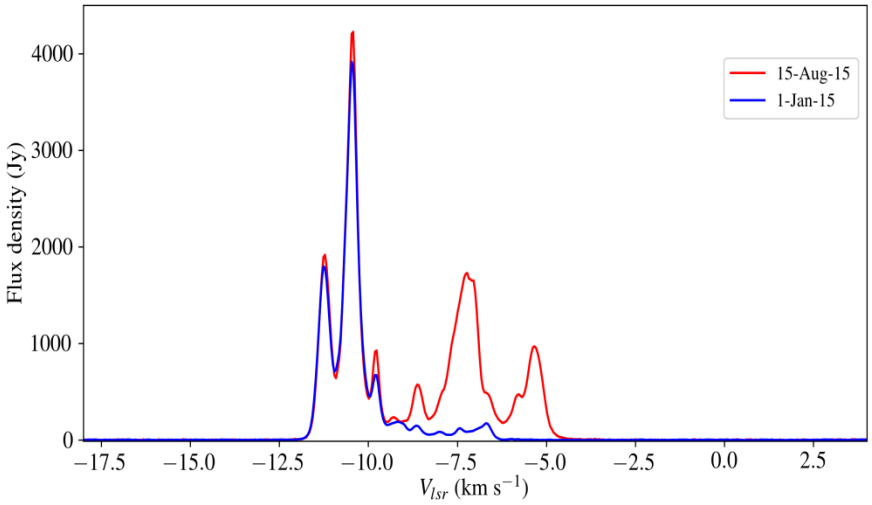
National Research Foundation

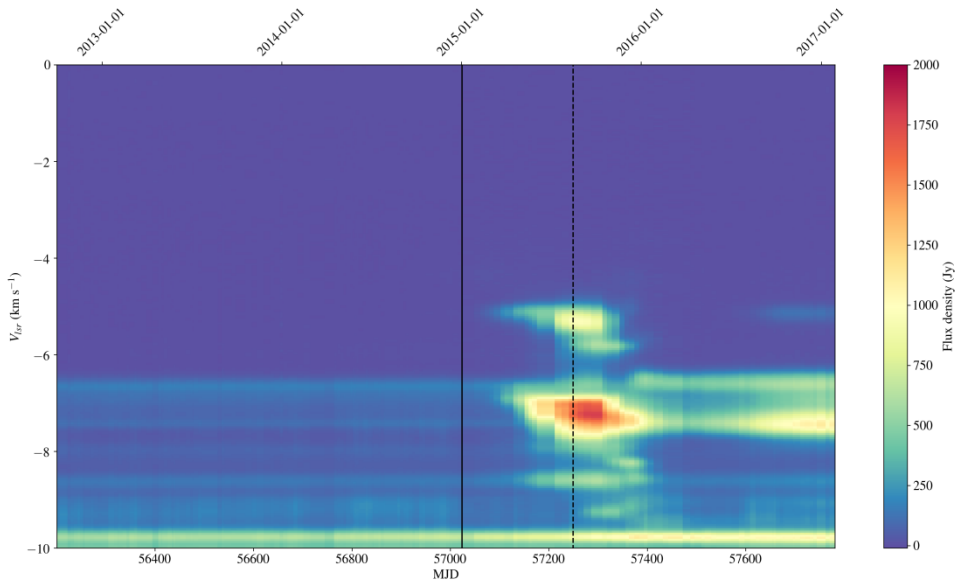
HartRAO
Hartebeesthoek Radio Astronomy Observatory

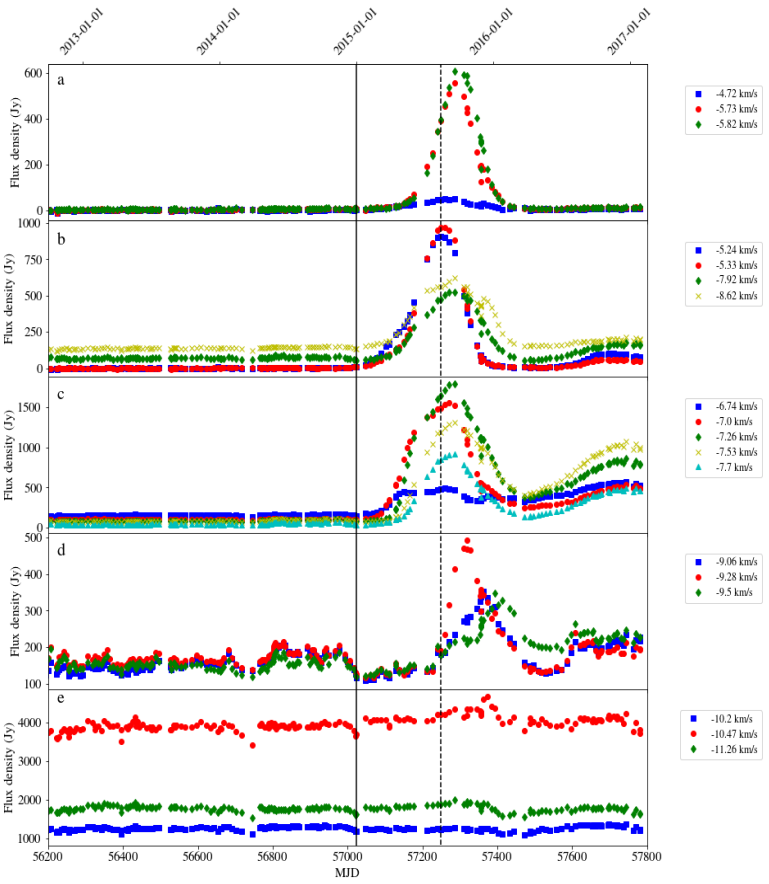
Massive Star-Formation

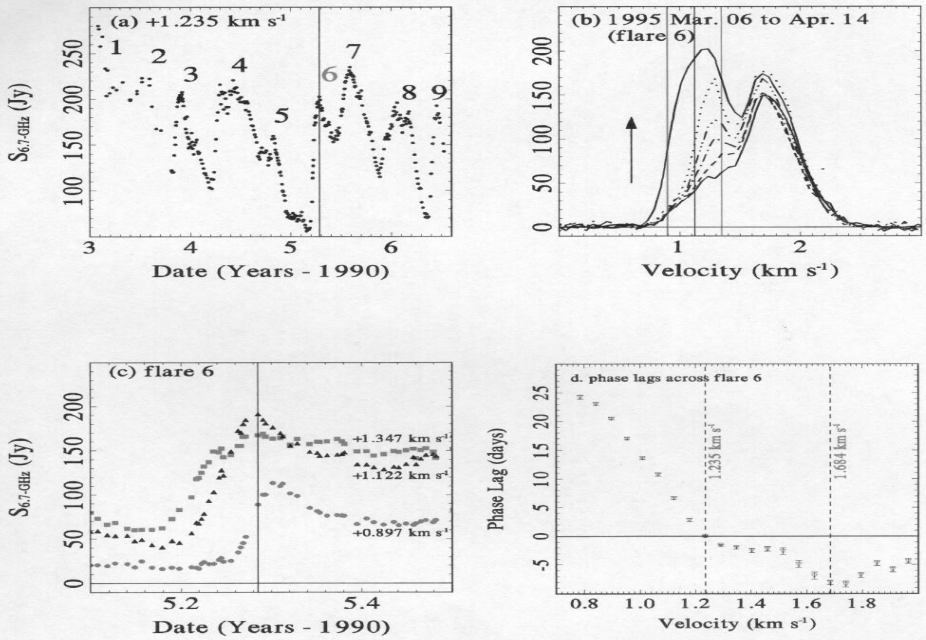


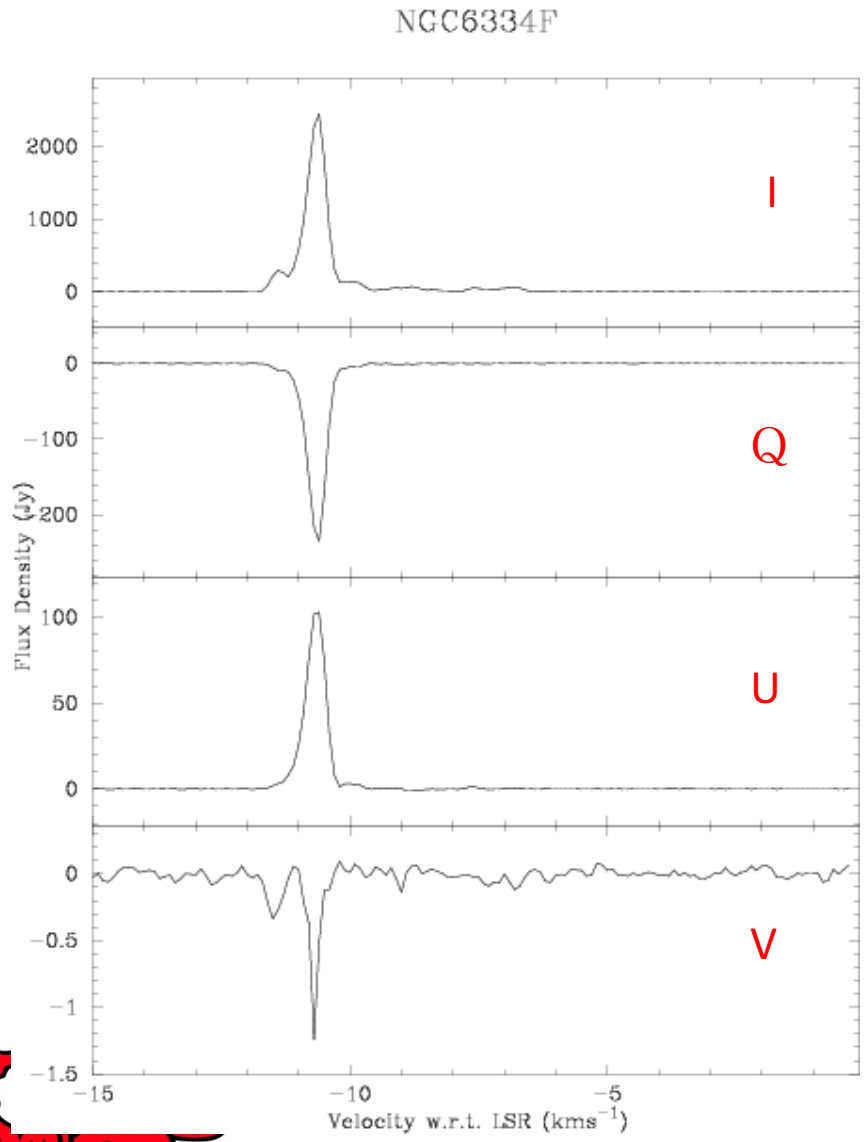
Kitty Event in NGC6334F; 6.7 GHz

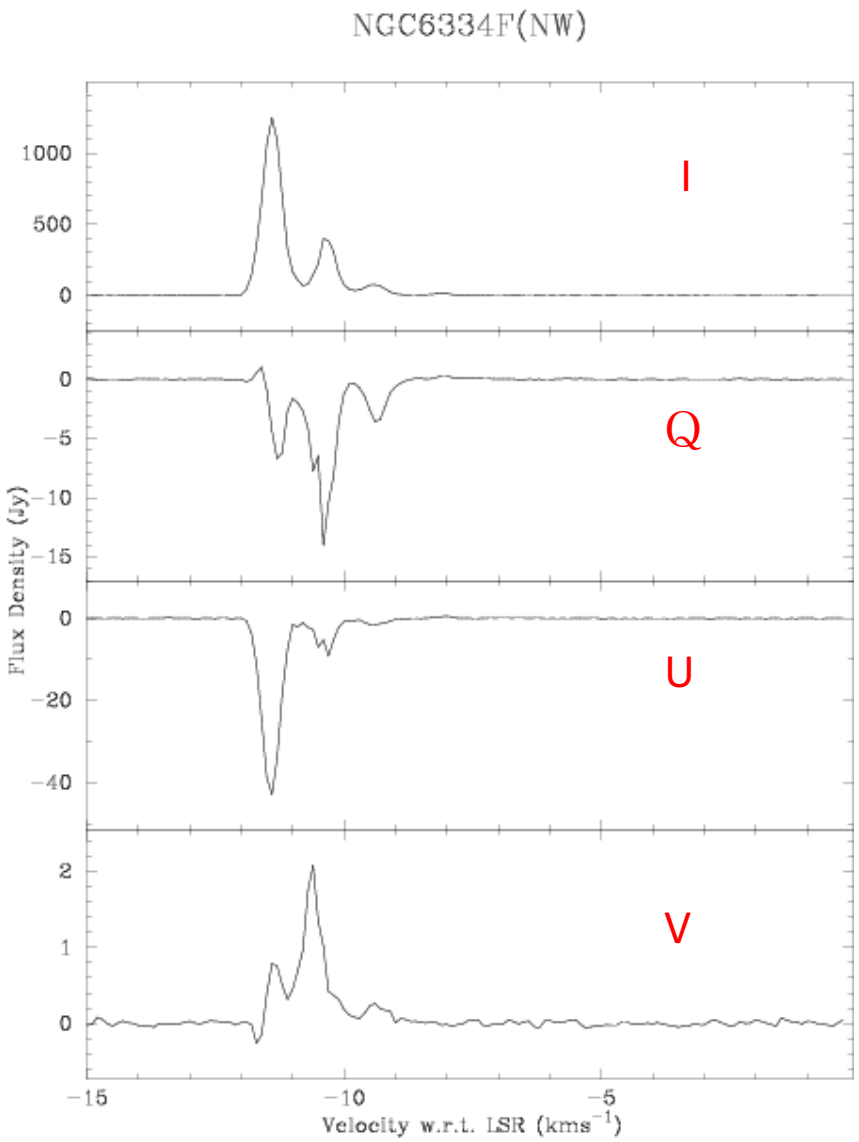




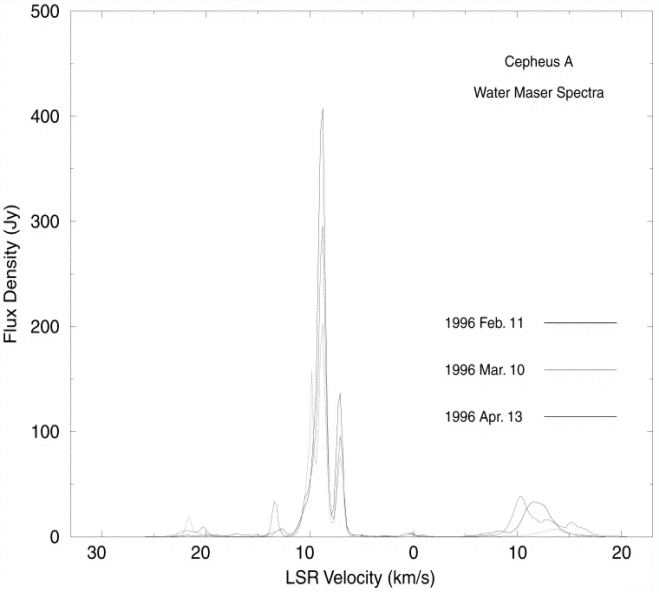



(a) +1.235 km s-1
1
2
3
4
5
6
7
8
9
S6.7-GHz (Jy)
Date (Years - 1990)
(b) 1995 Mar. 06 to Apr. 14
(flare 6)
Velocity (km s-1)
(c) flare 6
+1.347 km s-1
+1.122 km s-1
+0.897 km s-1
S6.7-GHz (Jy)
Date (Years - 1990)
d. phase lags across flare 6
1.235 km s-1
1.684 km s-1
Phase Lag (days)
Velocity (km s-1)





From the top : Stokes I, Q, U and V

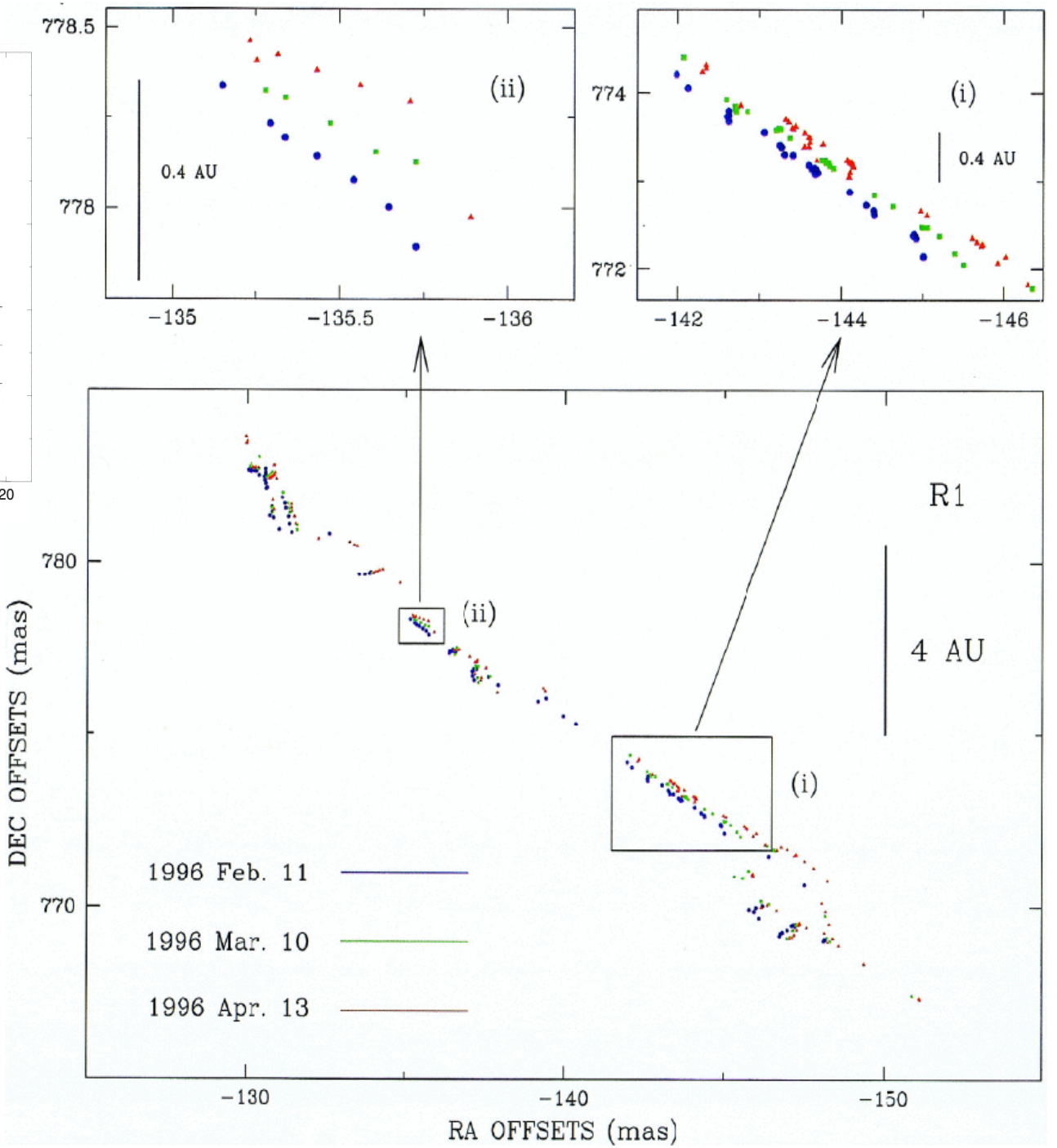


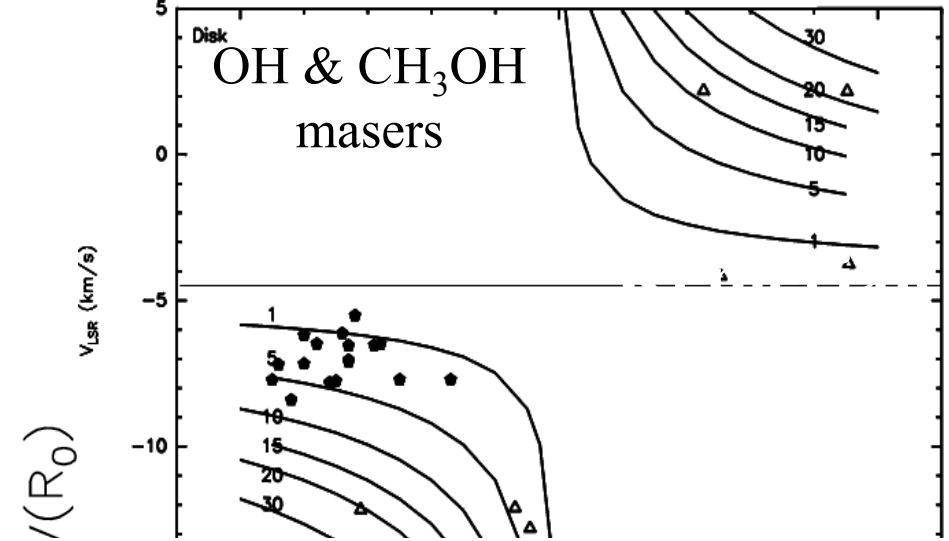
Proper motions of

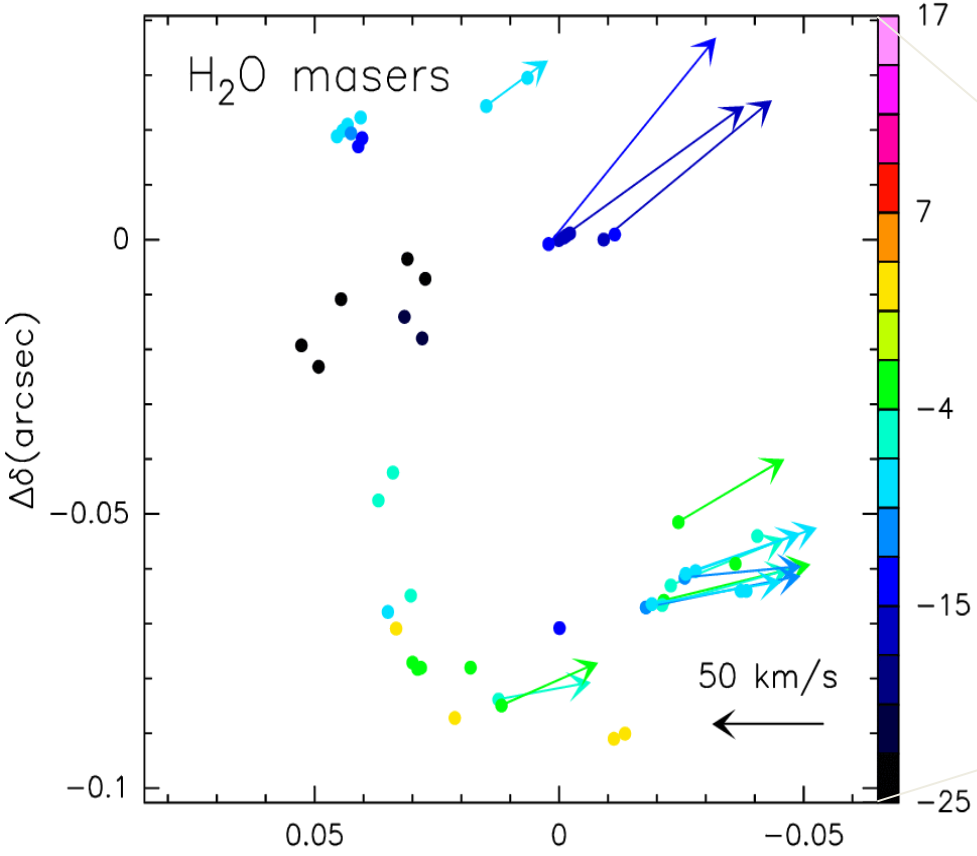
H_2O maser spots

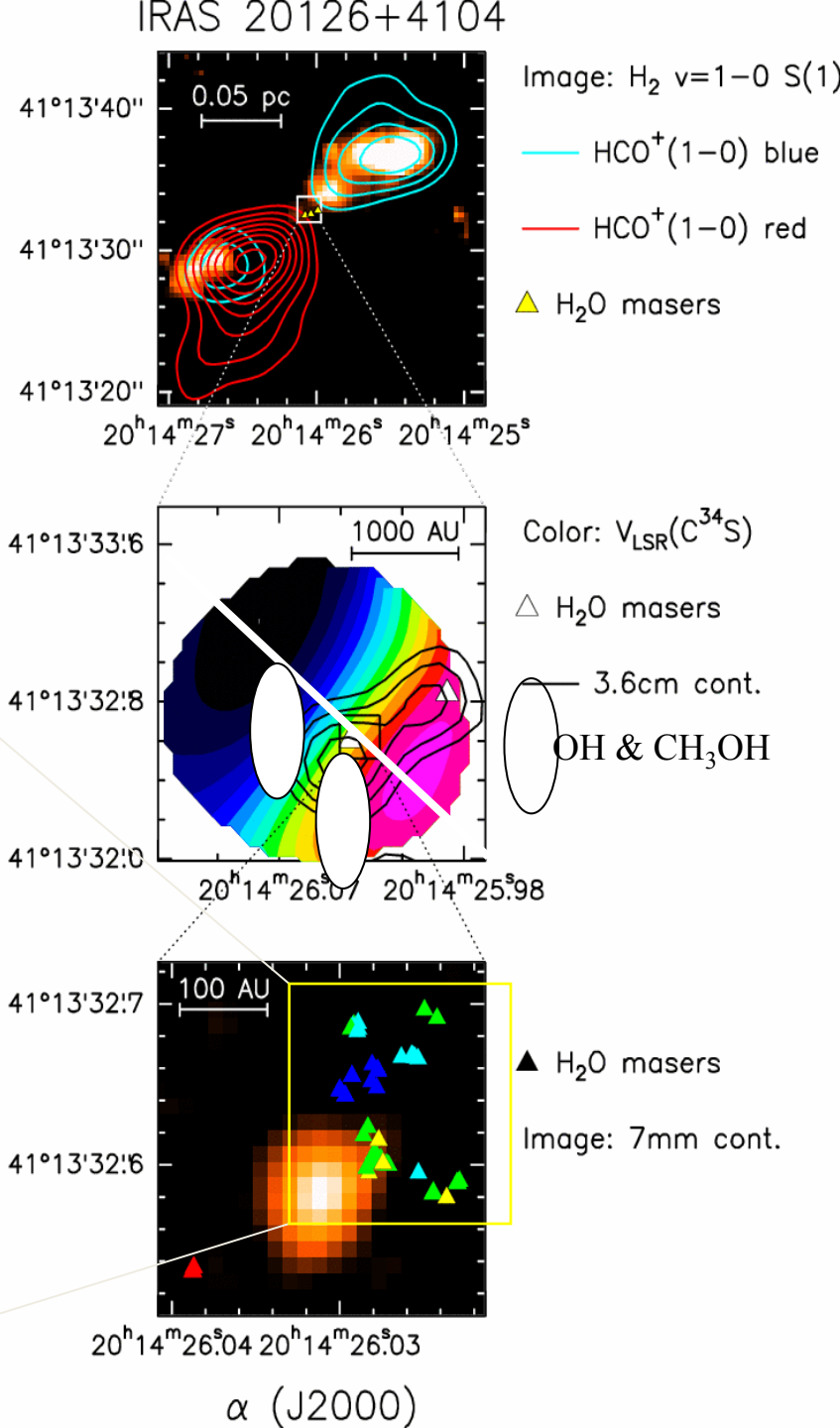
in star forming region

Torrelles et al. (2001)




OH & CH3OH
masers
Disk
30
20
15
10
5
1
1
5
10
15
20
30
VLSR (km/s)
/(R0)

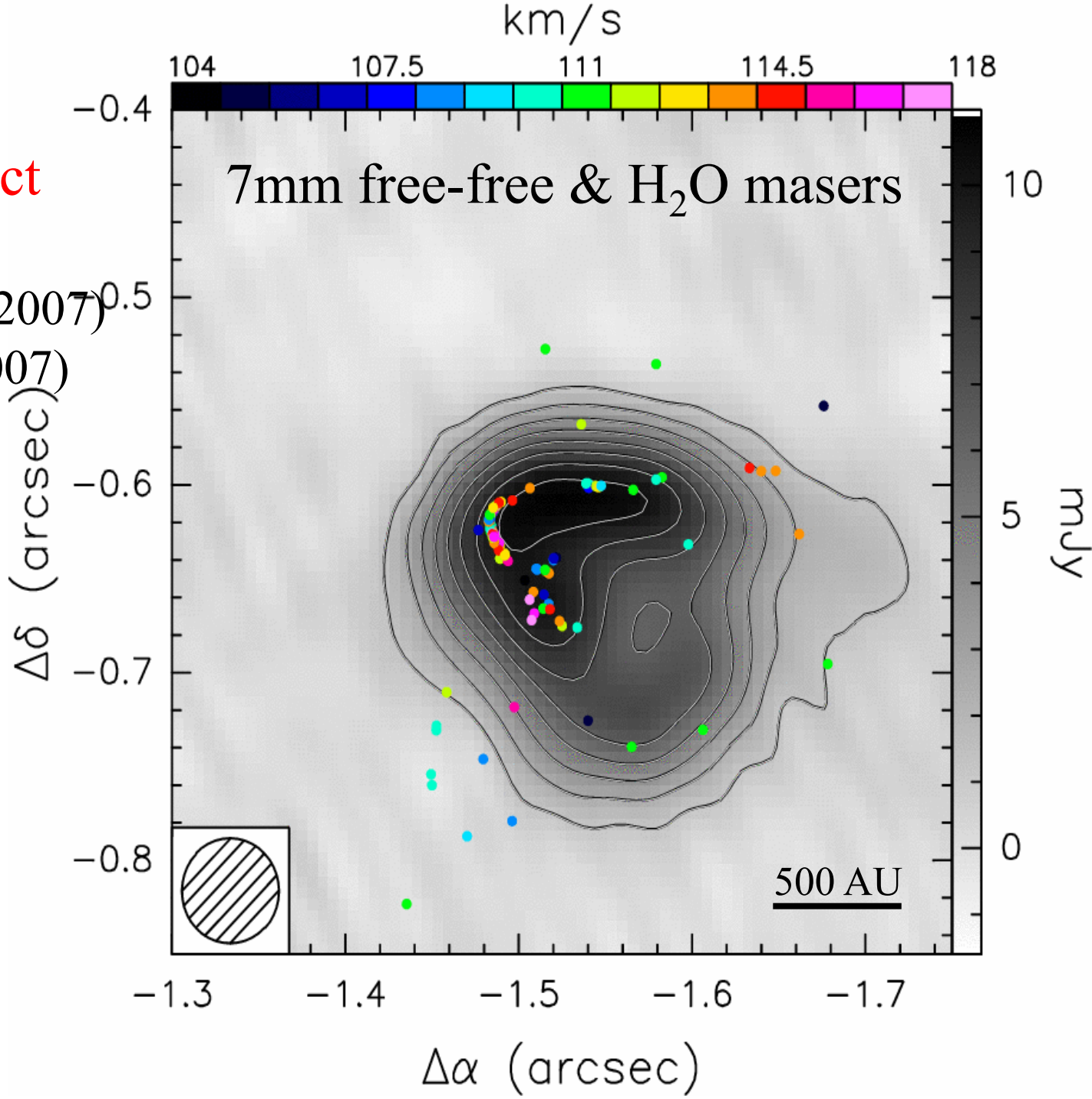

H2O masers
50 km/s
17
7
−4
−15
−25
VLSR (km/s)
0.05
0
−0.05
−0.1
Δδ(arcsec)


IRAS 20126+4104
0.05 pc
Image: H2 v=1−0 S(1)
HCO+(1−0) blue
HCO+(1−0) red
H2O masers
41°13'40"
41°13'30"
41°13'20"
20h14m27s 20h14m26s 20h14m25s
1000 AU
Color: VLSR(C34S)
H2O masers
3.6cm cont.
OH & CH3OH
41°13'33:6
41°13'32:8
41°13'32:0
20h14m26.07 20h14m25.98
100 AU
H2O masers
Image: 7mm cont.
41°13'32:7
41°13'32:6
20h14m26.04 20h14m26.03
δ (J2000)
α (J2000)

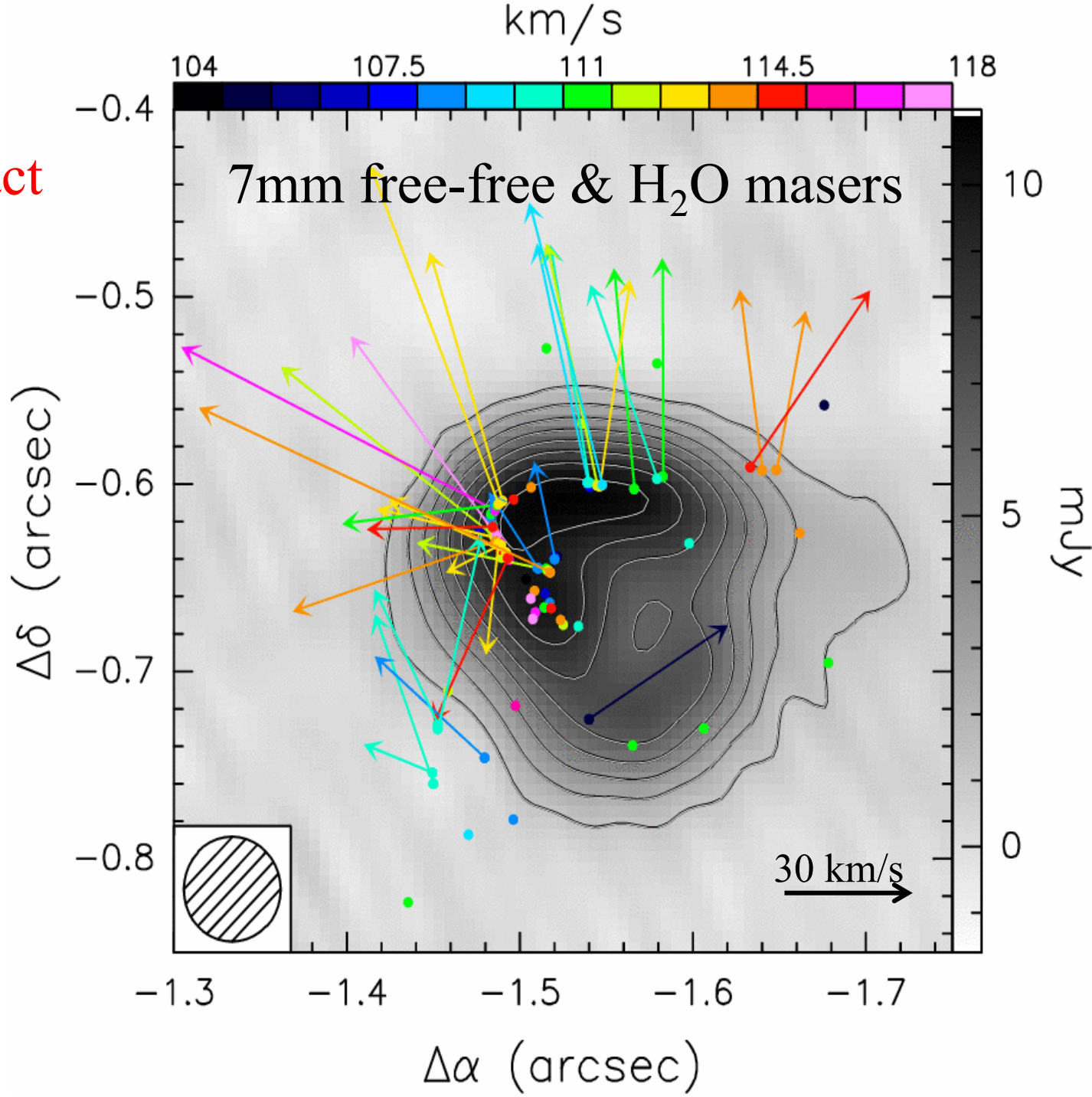
Hypercompact
HII region

Moscadelli et al. (2007)

Beltran et al. (2007)



Hypercompact HII region **expands!**



science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

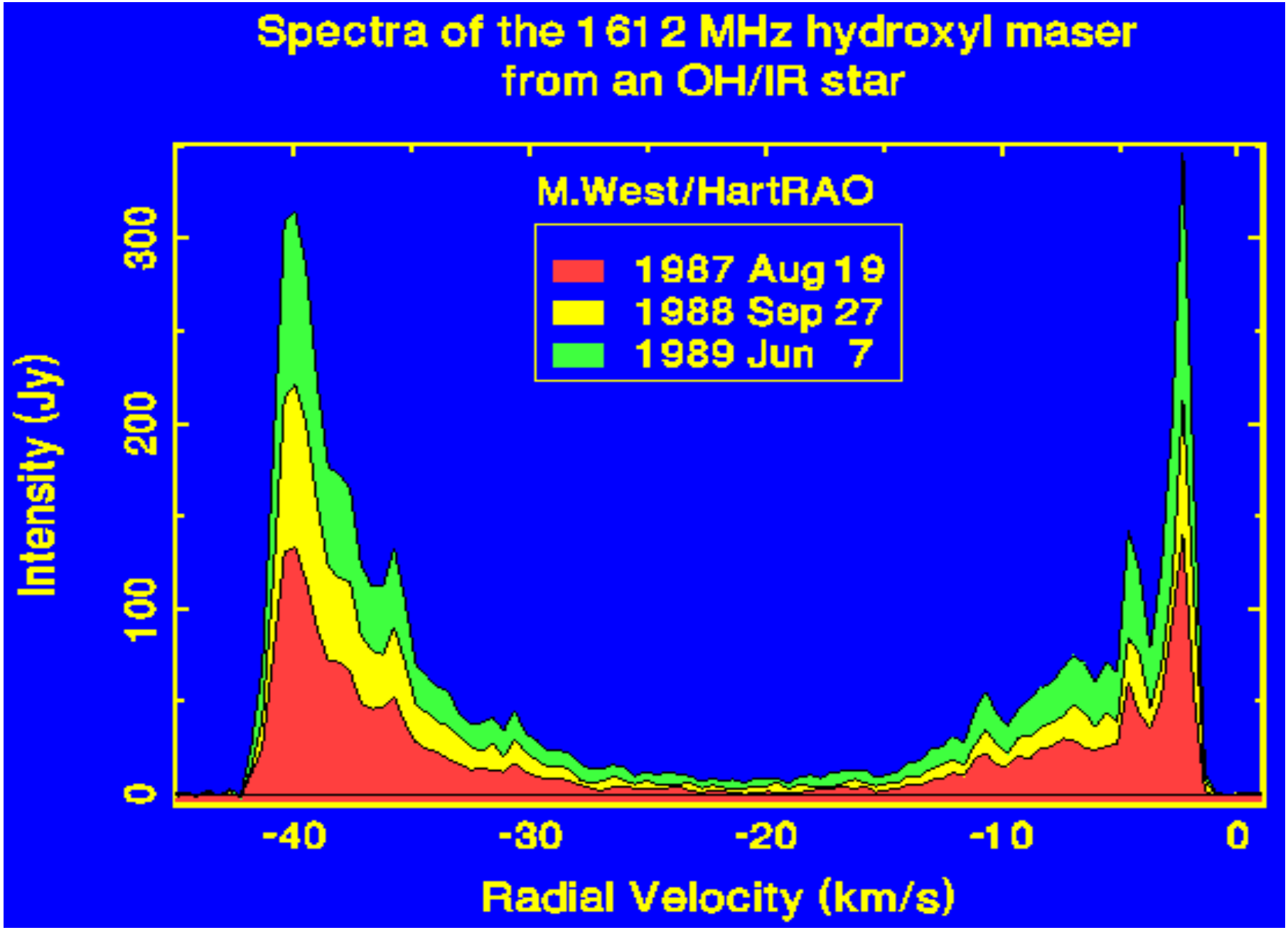
NRF
National Research Foundation

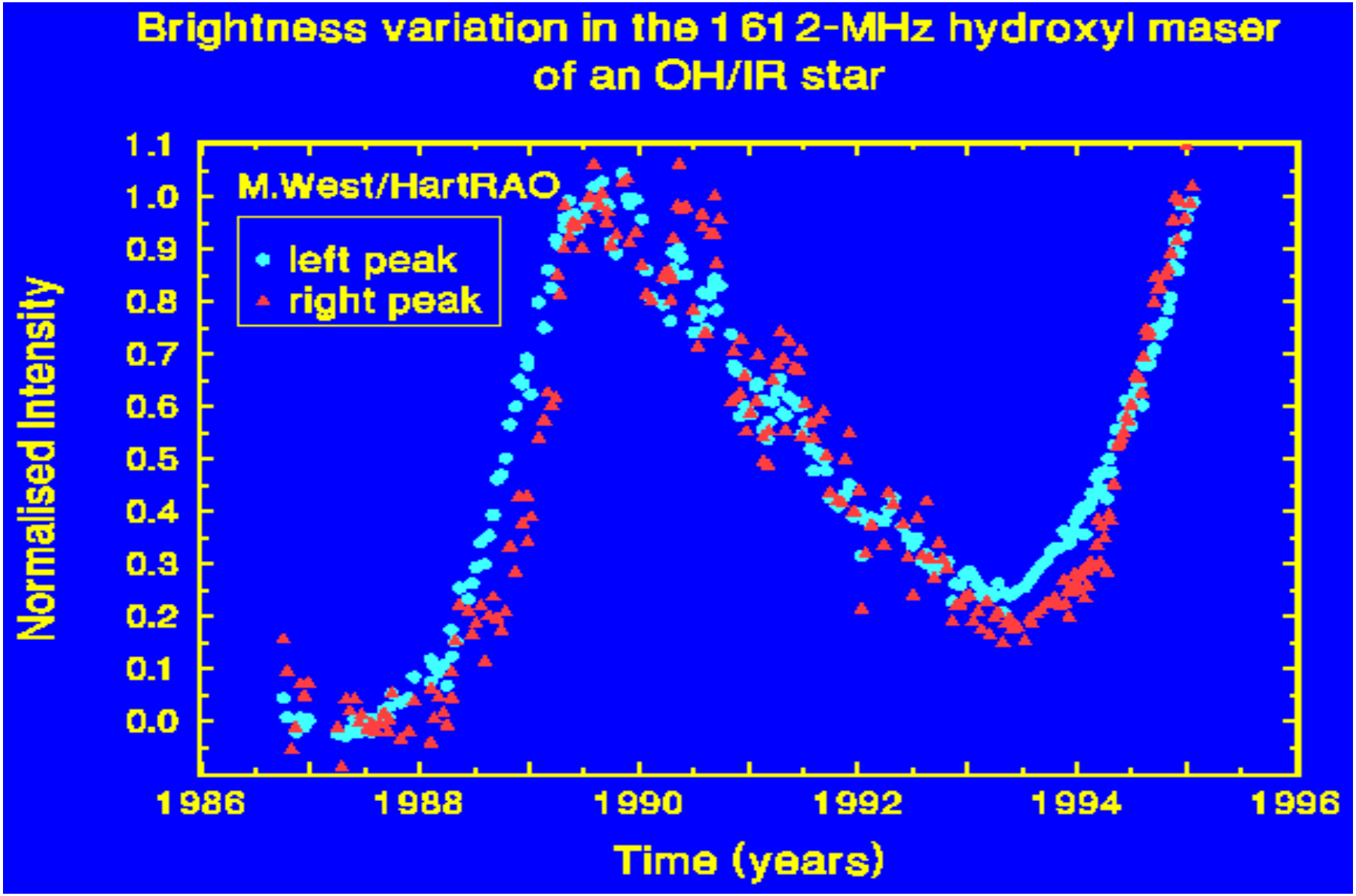
HartRAO
Hartebeesthoek Radio Astronomy Observatory

OH/IR Stars

HartRAO
The heartbeat of astronomy

SKA AFRICA
SQUARE KILOMETRE ARRAY


Spectra of the 1612 MHz hydroxyl maser
from an OH/IR star
M.West/HartRAO
1987 Aug 19
1988 Sep 27
1989 Jun 7
Intensity (Jy)
0
100
200
300
-40
-30
-20
-10
0
Radial Velocity (km/s)


Brightness variation in the 1612-MHz hydroxyl maser of an OH/IR star
M.West/HartRAO
left peak
right peak
Normalised Intensity
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1986
1988
1990
1992
1994
1996
Time (years)