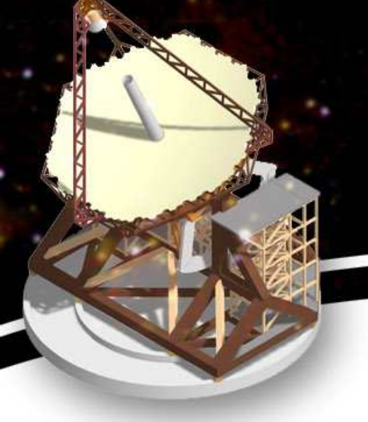
Three topics in star formation

1. The Initial Mass Function of Star Formation in Massive Clusters

Stephen Strom, Knut Olsen, Joan Najita, and Robert Blum

GSMT SWG and ESO ELT SWG Joint Meeting
May 17, 2004

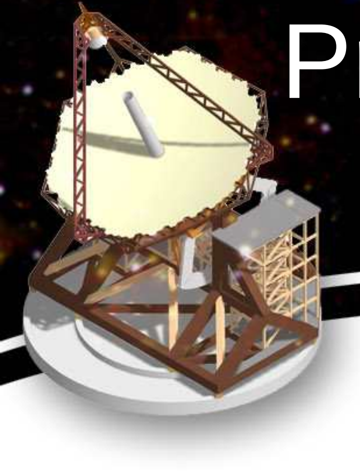
GEMINI



Probing the IMF: Goals

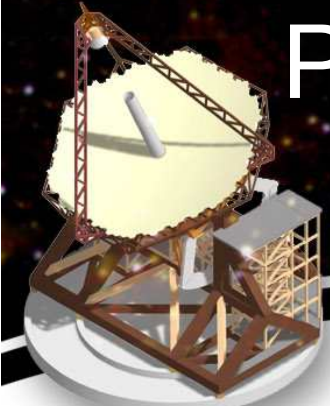
- Quantify the IMF in rich, dense star-forming regions
  - dominant contributor to total stellar content of galaxies
- Understand the relationship between IMF; initial conditions

Critical to modeling star-formation in the early universe



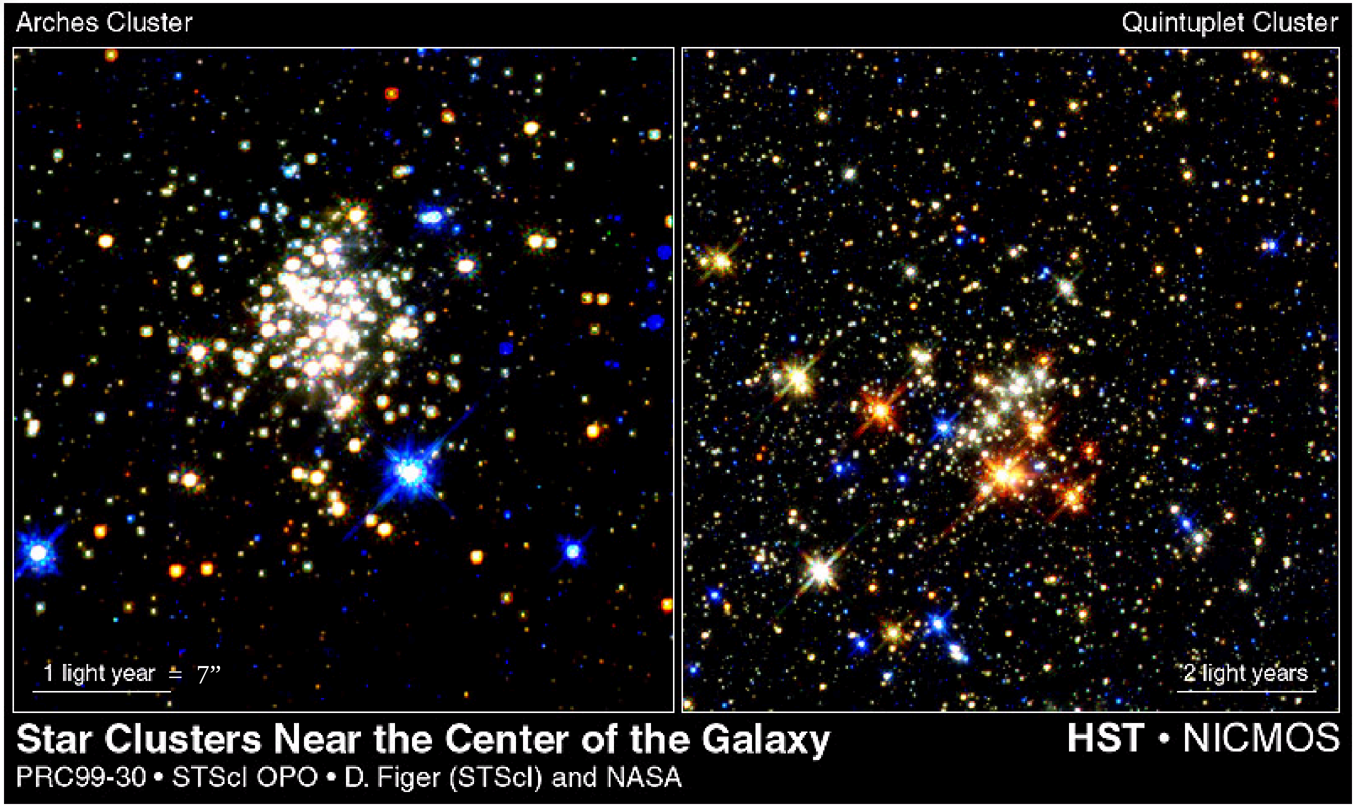
Probing the IMF: Measurements

- JHK photometry
  - – MCAO images at high Strehl (~ 0.7 at K-band)
- IFU spectroscopy at R ~ 1000 provides spectral types
- Spectral types + photometry yield:
  - $N(A_v)$
  - statistical model of N(K)
  - N (M) for assumed age



Probing the IMF: Measurements

Galactic Center Superclusters: d = 10 kpc


Arches Cluster

Quintuplet Cluster

Star Clusters Near the Center of the Galaxy

HST • NICMOS

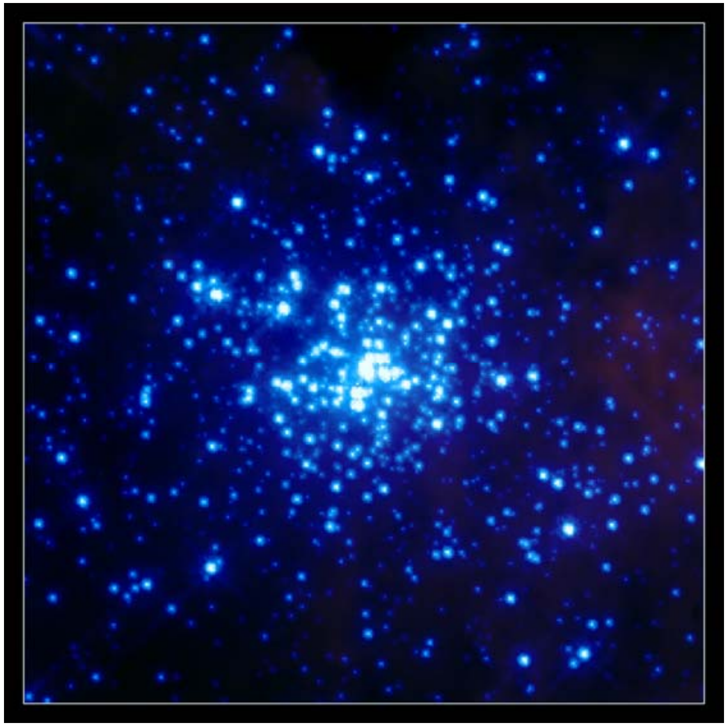
PRC99-30 • STScI OPO • D. Figer (STScI) and NASA

Stellar density ~ 100x Orion Nebula Cluster

Probing the IMF: Measurements

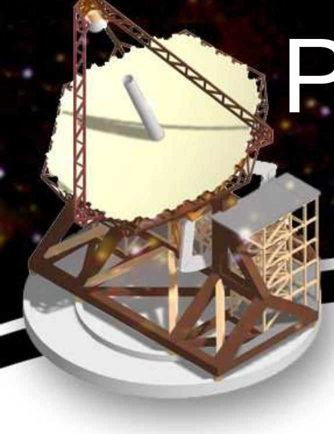
LMC Massive Cluster: d = 200 kpc

20”



R 136

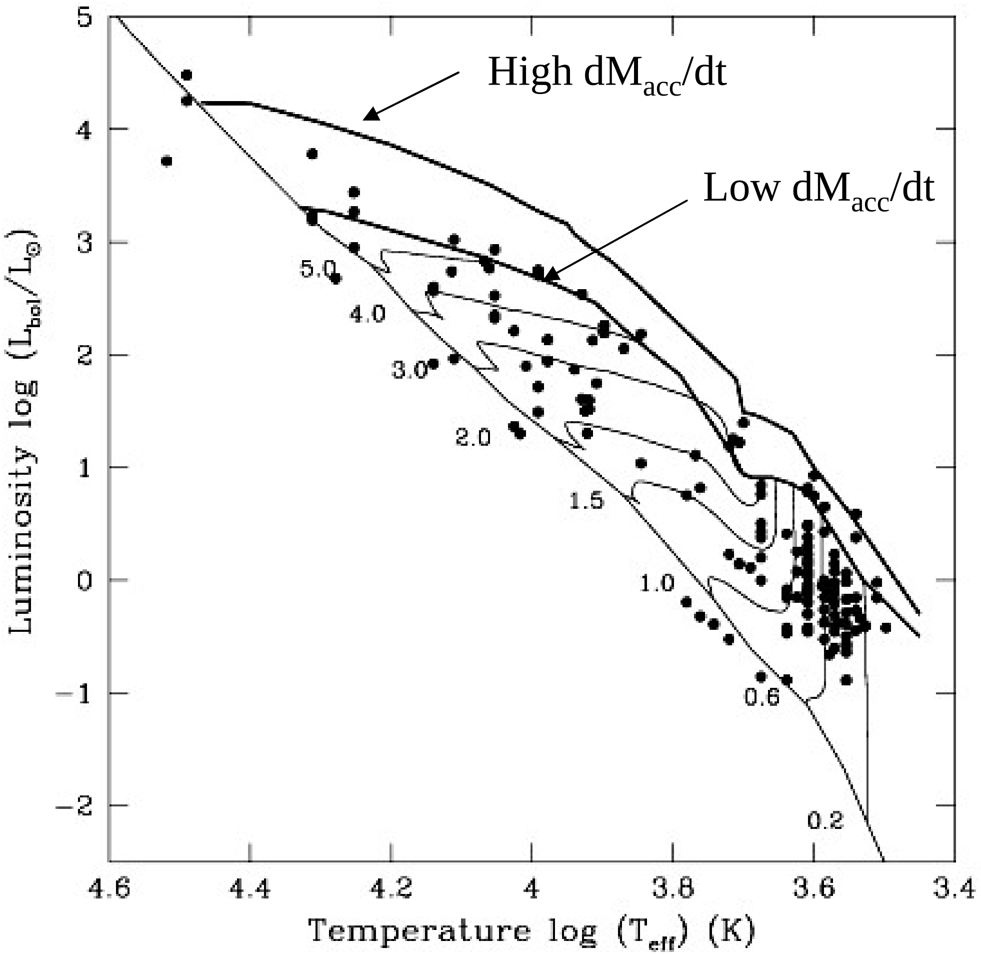
Stellar density ~ 10x Orion Nebula Cluster



Probing the IMF: Measurements

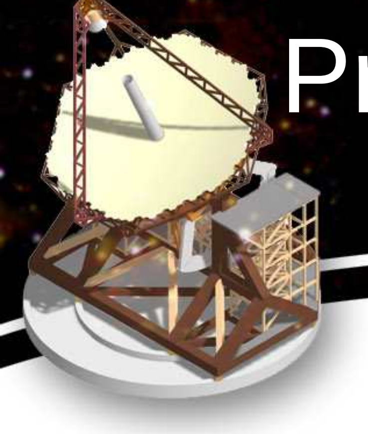
Stellar Birthlines for Differing dM_{acc}/dt

How is dM_{acc}/dt related to [Fe/H]; stellar density?



High dM_{acc}/dt

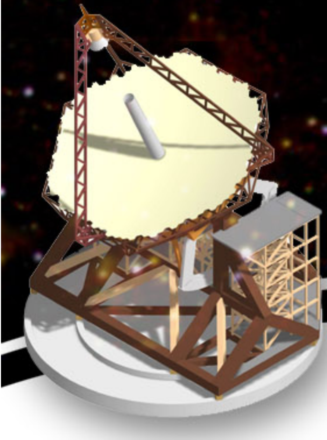
Low dM_{acc}/dt



Probing the IMF: Current Status

- Best available data: HST probes of Arches (MWG); R136 (LMC)
  - – IMF range limited to $M > 2\ M_{sun}$

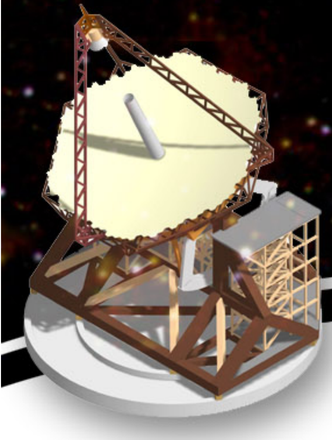
- With JWST or MCAO on 8-m telescopes
  - – IMF can be probed down to hydrogen-burning limit in MWG
  - – Studies in more distant galaxies in Local Group (~1 Mpc) not feasible
    - Crowding limits photometric measurements



Results: 8-m

	Limiting K-magnitude			Limiting Mass			Exposure Time		
Radius (R_e)	**LMC**	**M33**	**M82**	**LMC**	**M33**	**M82**	**LMC**	**M33**	**M82**
0.5	**16.3**	**<16.5**	**<19.8**	**13**	**>200**	**>200**	**0.01**	**0.01**	**<3**
1.0	**24.6**	**<16.5**	**<19.8**	**0.25**	**>200**	**>200**	**10000**	**0.01**	**<3**
2.0	**24.6**	**17.2**	**<19.8**	**0.25**	**150**	**>200**	**10000**	**0.03**	**<3**
5.0	**24.6**	**21.5**	**<19.8**	**0.25**	**20**	**>200**	**10000**	**40**	**<3**

does not reach M33, M82

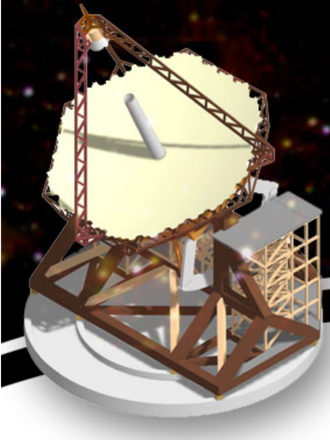


Results: 30-m GSMT R136-like Cluster

	Limiting K-magnitude			Limiting Mass			Exposure Time		
Radius (R_e)	LMC	M33	M82	LMC	M33	M82	LMC	M33	M82
0.5	>27.5	17	<19.8	~0.01	170	>200	12000	0.0	0.03
1.0	>27.5	18.9	<19.8	~0.01	65	>200	12000	0.01	0.03
2.0	>27.5	22.3	20	~0.01	3	193	12000	1.5	0.04
5.0	>27.5	27.5	23.9	~0.01	1.1	32	12000	12000	25

OK for the Local Group

We have also calculated spectroscopic exposure times, but they are not shown here

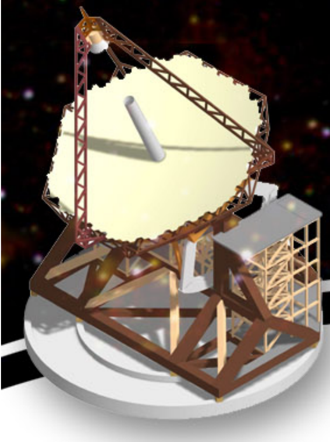


Results: 100-m

AURA NEW INITIATIVES OFFICE

	Limiting K-magnitude			Limiting Mass			Exposure Time		
Radius (R_e)	**LMC**	**M33**	**M82**	**LMC**	**M33**	**M82**	**LMC**	**M33**	**M82**
0.5	**>27.5**	**15.5**	**<19.8**	**~0.01**	**20**	**>200**	**100**	**<0.01**	**<0.01**
1	**>27.5**	**26.5**	**19.8**	**~0.01**	**1.8**	**200**	**100**	**17**	**<0.01**
2.0	**>27.5**	**>33.5**	**25.3**	**~0.01**	**~0.01**	**25**	**100**	**10000 @ K=30**	**2**
5.0	**>27.5**	**>33.5**	**>36.8**	**~0.01**	**~0.01**	**~0.01**	**100**		

reaches M81 and Cen groups too



Conclusions:IMF

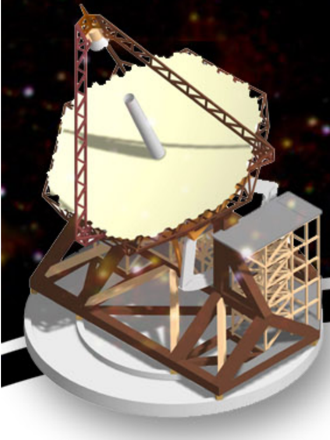
- GSMT can establish the link between emerging stellar populations and initial conditions in star-forming regions
  - Fundamental to understanding star-formation process
  - Essential to understanding galactic evolution

- Size matters!
  - Crowding limits photometric accuracy
  - Crowding limit scales as d^2
  - Telescope diameters of 30m or greater are needed

- The IMF example is representative of a large class of problems that require superb image quality over ~1’ FOV

2. Characterizing Extra-Solar Planets

J. Lunine, J. Najita and S. Strom



OVERVIEW

Goal: Characterize exo-planets

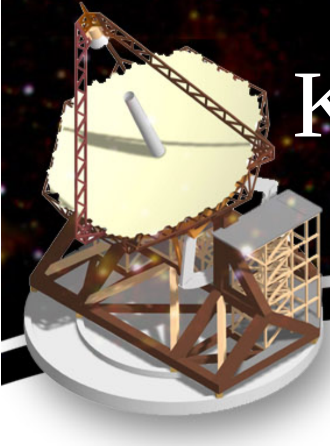
- Atmospheric structure; chemistry; rotation; “weather”
- Determine formation mechanism for EGPs

Measurements: R~ 10 photometry & R ~ 200 spectra

- Near-infrared (reflected light)
- Mid-infrared (thermal emission)

Role of GSMT: Enable measurements via

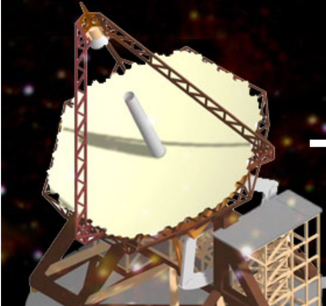
- High sensitivity
- High angular resolution



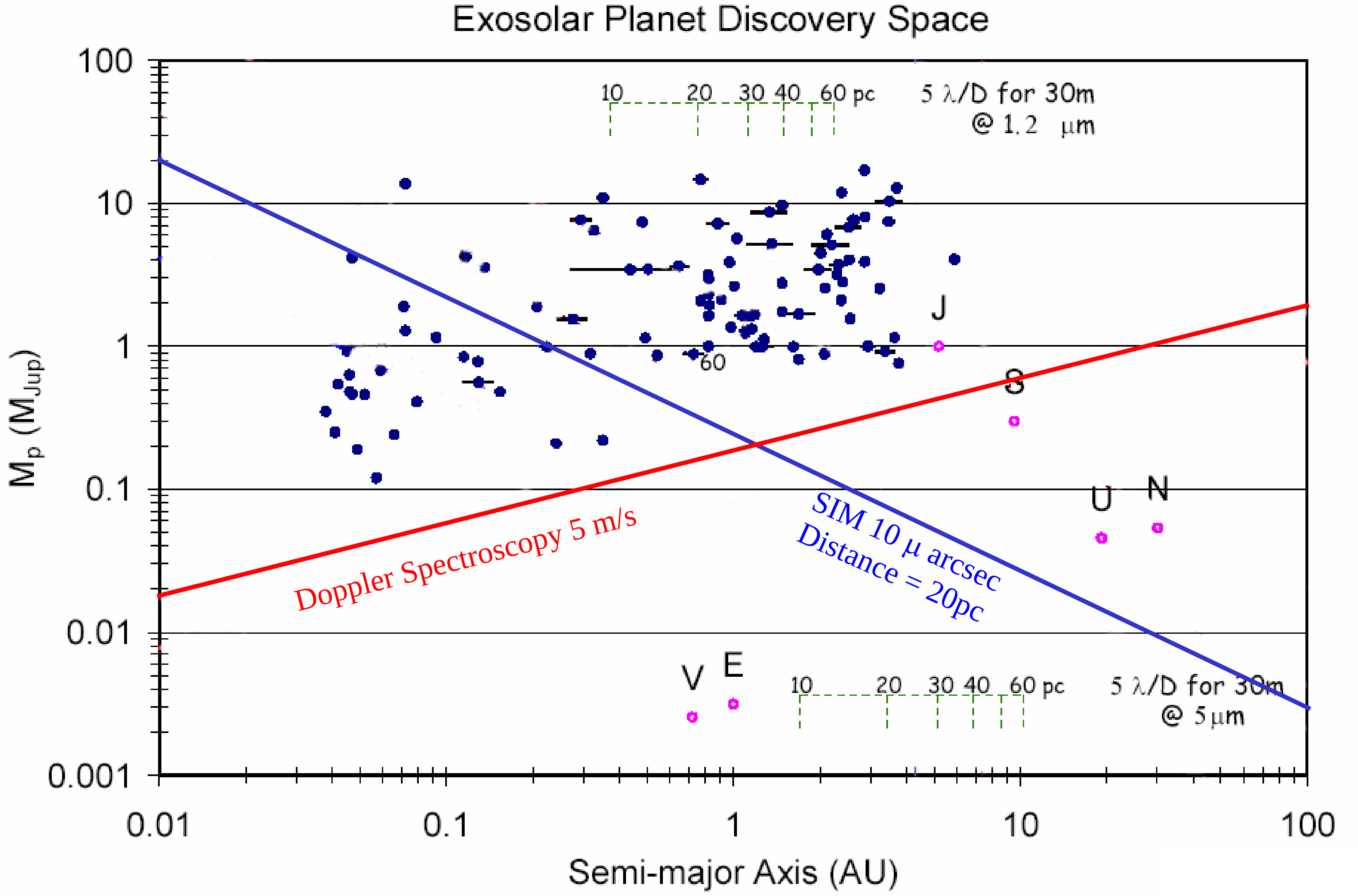
KEY PARAMETERS: 30m GSMT

λ	**$5\lambda/D$**	**Separation @ 10pc**
1.2 μ	40 mas	0.4 AU
4.7 μ	160 mas	1.6 AU

Aperture is critical to enable separation of planet from stellar image. 100 m telescope => much larger sample

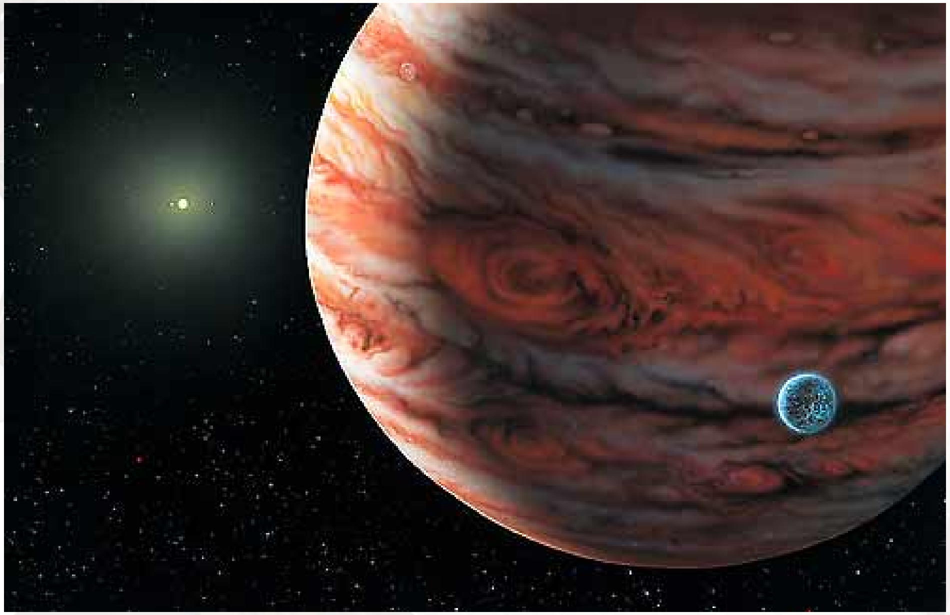


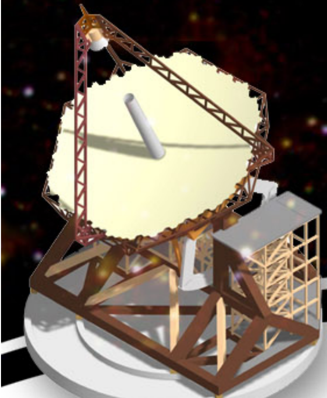
The Realm of 30m Telescopes



Exosolar Planet Discovery Space

xo-Jupiter Ex

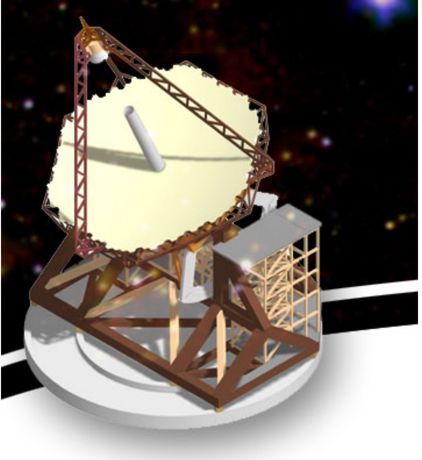


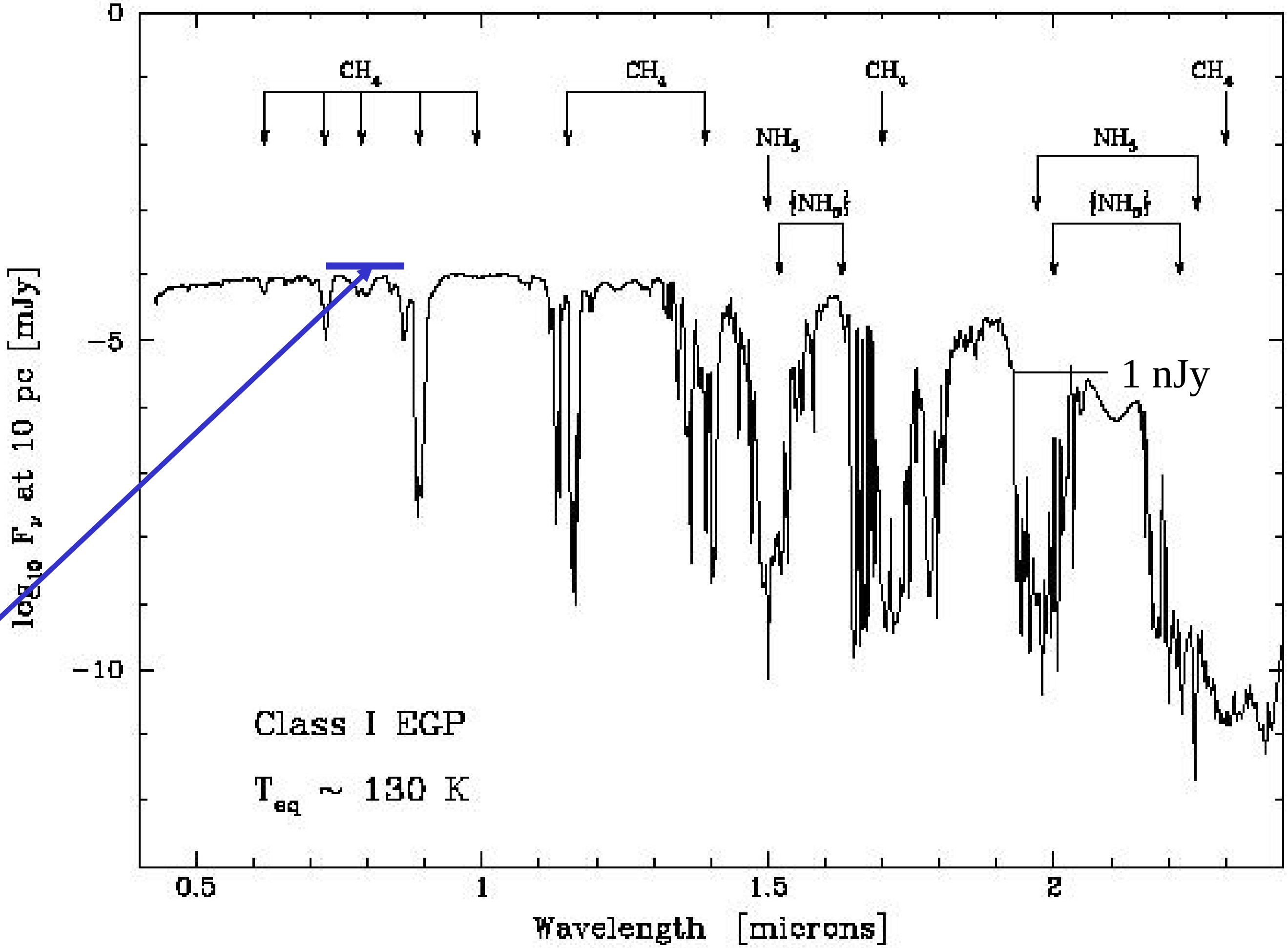


Goals

- Image planet at multiple wavelengths (R ~ 10)
- Classify planet from broad spectral features (R ~ 100)
- Analyze atmospheric structure and chemistry (R ~ 1000)
- Understand origin via (C,N,O)/H ratios
  - High metal abundance suggests an agglomeration origin
  - Low metal abundance suggests origin in disk instability
- Determine rotation & weather via synoptic observations

GEMINI

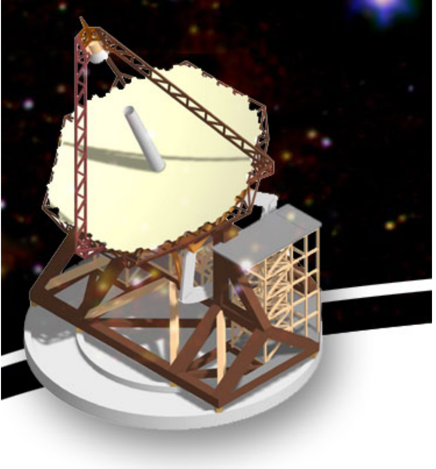


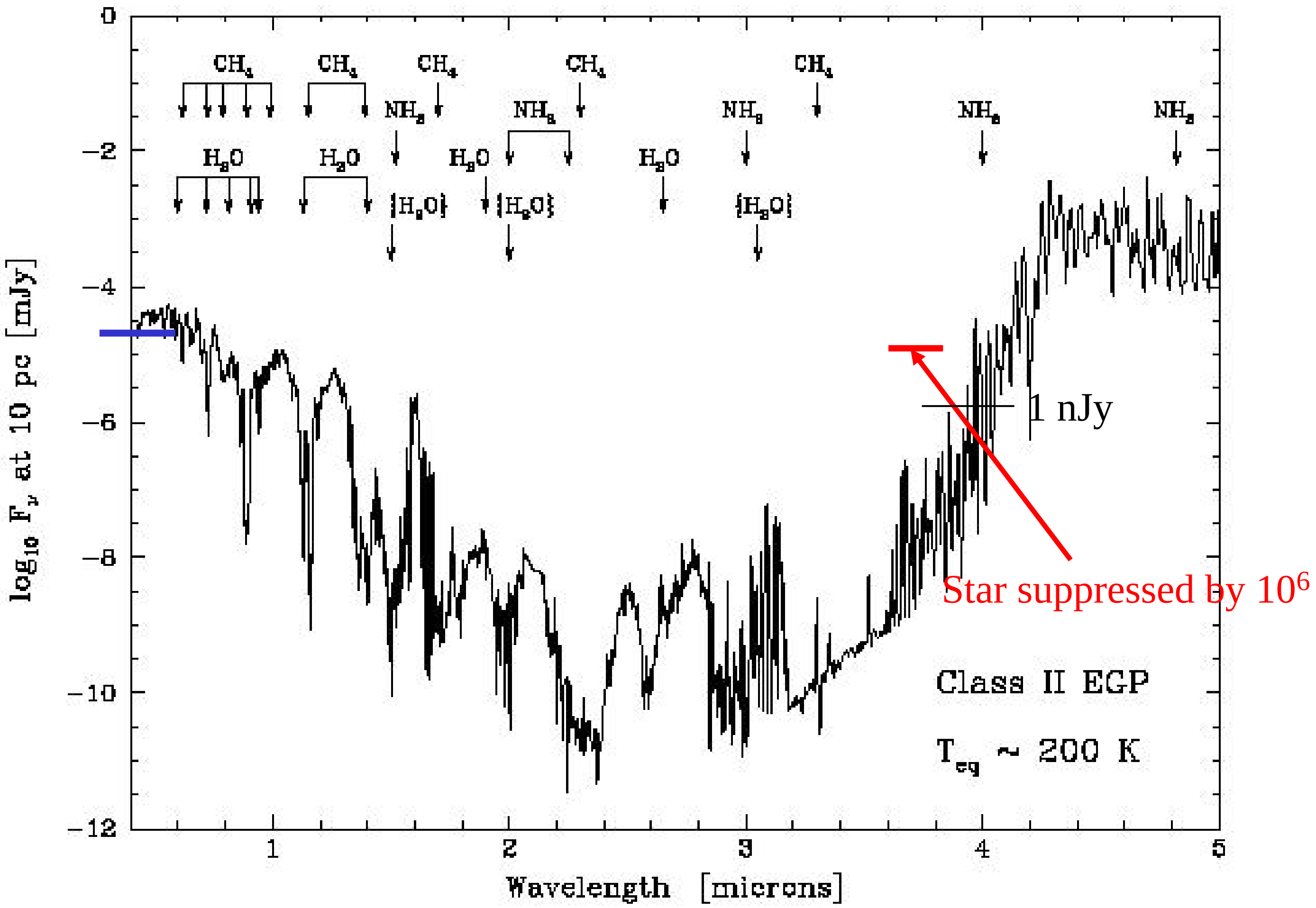


Star suppressed by 10^6

Class I EGP: Cold Jupiter Mass Planet at 5 AU

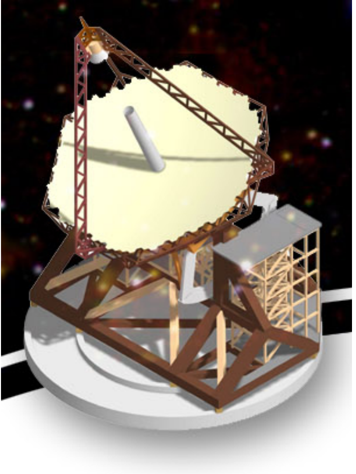
Ammonia Ice and Water Clouds produce high reflectivity in near IR

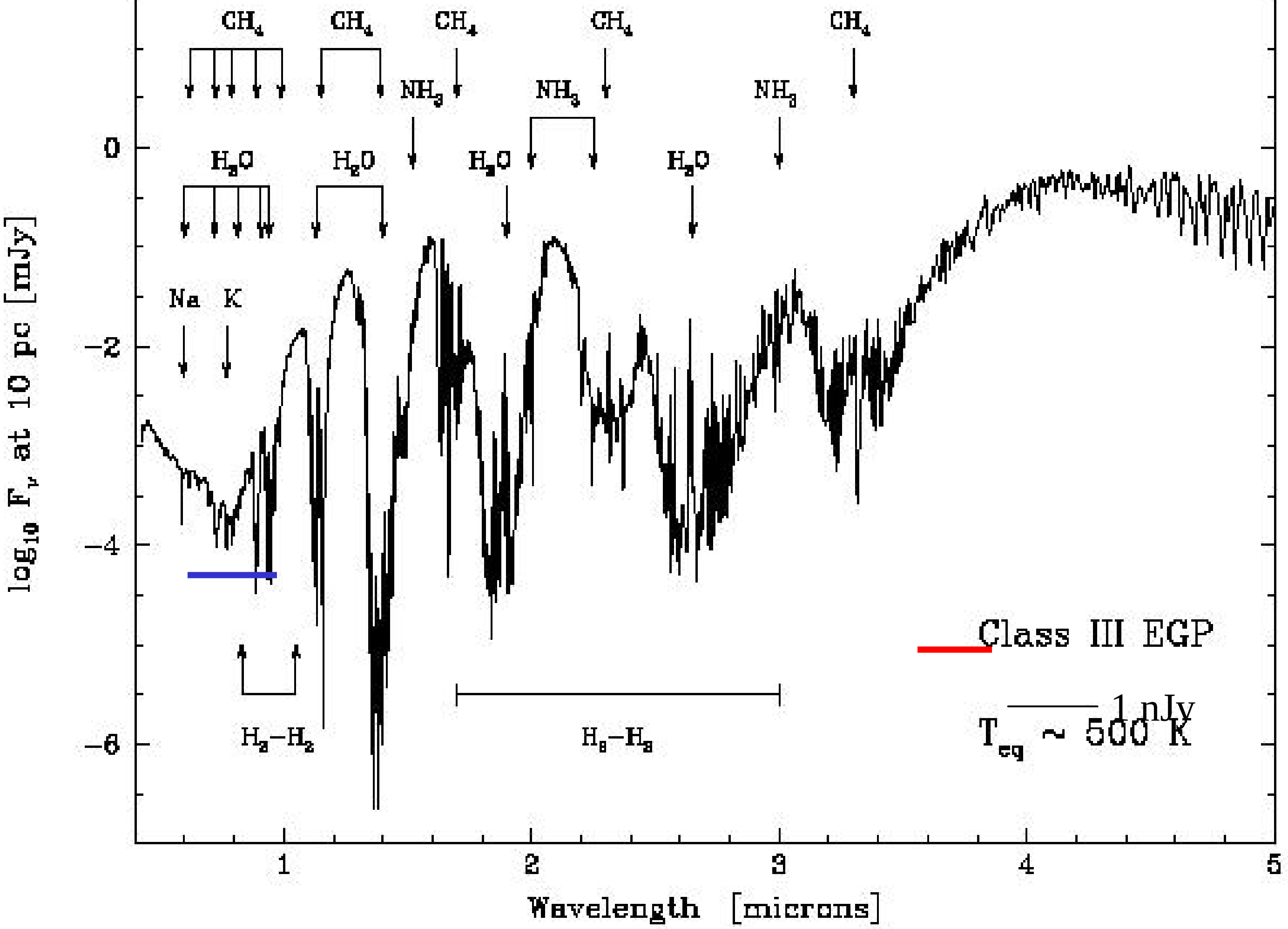




Class II EGP: Cool Jupiter-Mass Planet at 1.5 AU

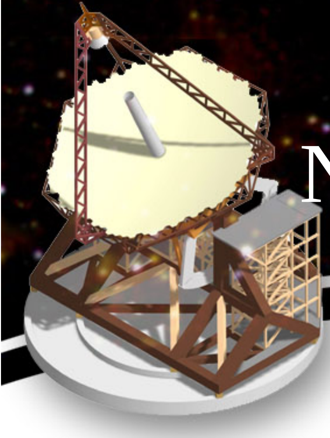
Ammonia gaseous; water clouds in troposphere, enhancing NIR reflectivity





Class III EGP: Warm Jupiter-Mass Planet at ~ 0.5 AU

Absorption by gaseous Water, Methane and Molecular Hydrogen Dominate

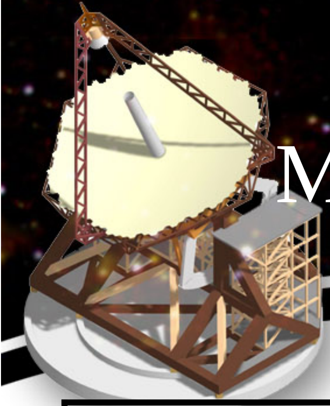


Near-IR Characterization of Exo-Jupiters

1.2 μm R ~ 10 S/N = 25

Object Class	Integration Time	Contrast Ratio
Class I (~5 AU) 32nJy @ 1.2 μm	1.5 hours	5x10^{8}
Class II (~1.5 AU) 1nJy @ 1.2 μm	1,500 hours	1.5x 10^{10}
Class III (~0.5 AU) 100nJy @ 1.2 μm	0.17 hours	1.5 x10^{6}

NB: Calculated times assume NO contribution from parent star



Mid-IR Characterization of Exo-Jupiters

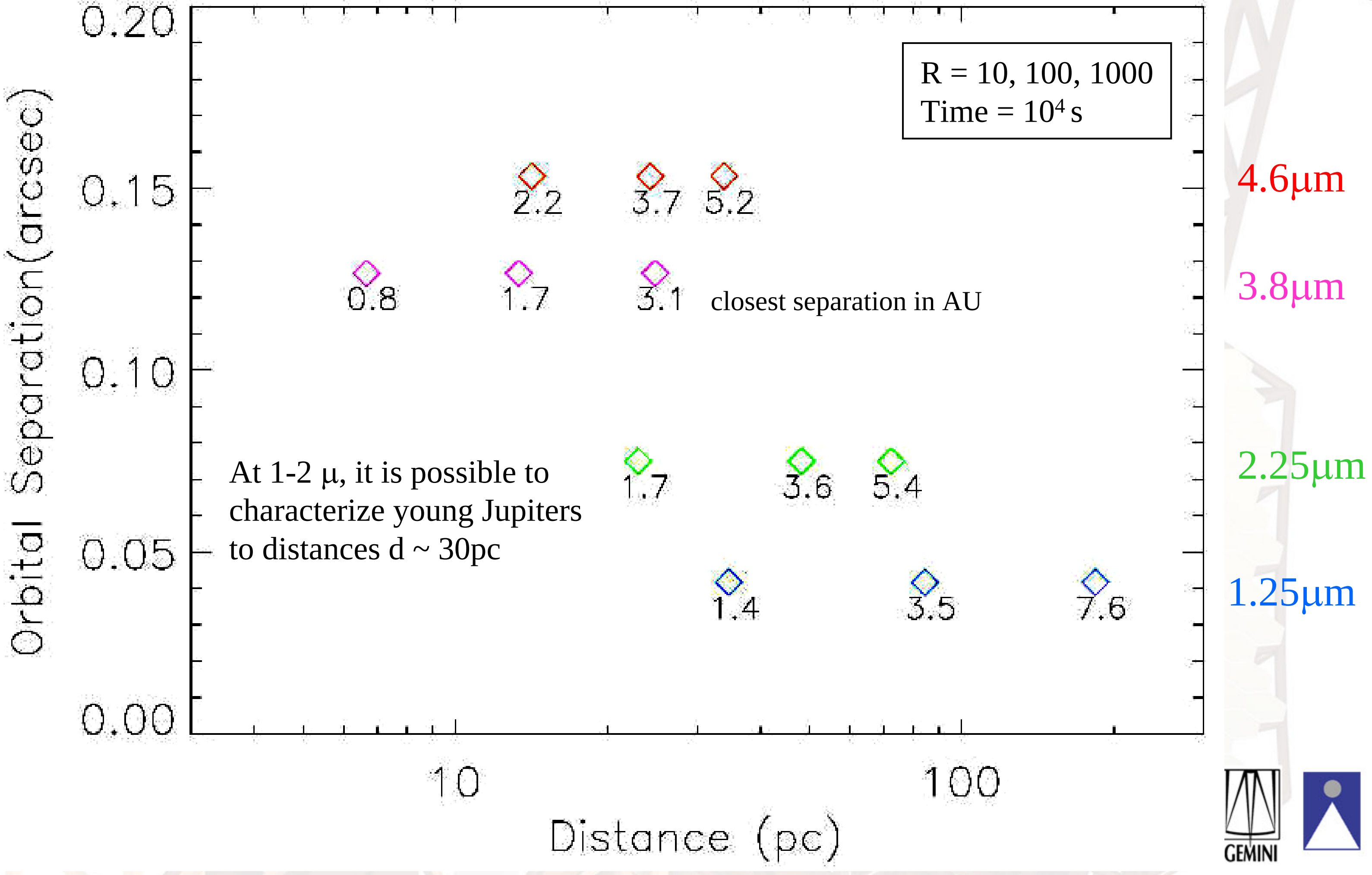
4.7 µm R ~ 10 S/N = 25

Object Class	**Integration Time** **GSMT R ~ 10**	**Contrast Ratio**	**Integration Time** **JWST R ~ 10**
Class I (~5 AU) 300nJy @ 4.7 µm	3,000 hours	2x10^7	0.2 hrs
Class II (~1.5 AU) 1000nJy @ 4.7 µm	250 hours	7x10^6	0.03 hrs
Class III (~0.5 AU) 30000nJy @ 4.7 µm	0.3 hours	2x10^5	3 seconds

NB: Calculated times assume NO contribution from parent star

Limiting Distance and Orbital Separation

1 M_J 100 Myr

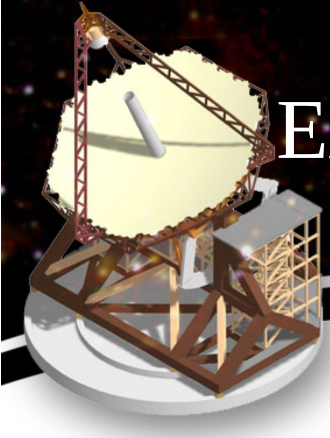


R = 10, 100, 1000
Time = 10^4 s

closest separation in AU

At 1-2 µ, it is possible to characterize young Jupiters to distances d ~ 30pc

B[illegible] Earths: Simple [illegible]

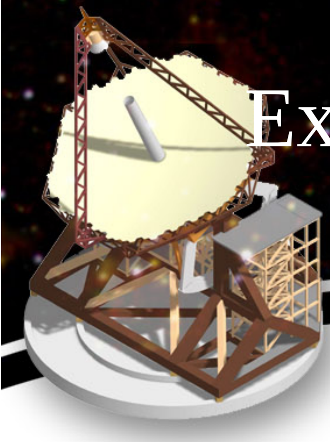


Exo-Earth Characterized via Scattered Light

1.2 µm R ~ 10 S/N = 25 Albedo ~ 0.5

Earth-Sun Distance	**Integration Time 30m GSMT**	**Contrast Ratio**	**Integration Time 100m OWL**
1 AU (5 nJy @ 1.2 µm)	61 hours	10^{10}	0.5 hours
0.4 AU (30nJy @ 1.2 µm)	2 hours	$2x10^{9}$	0.01 hours

NB: Calculated times assume NO contribution from parent star

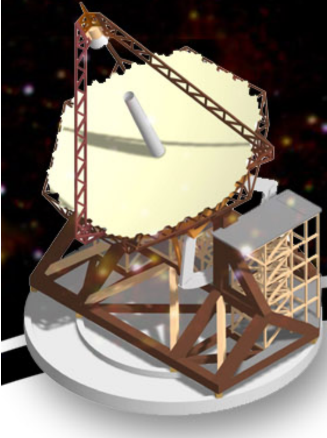


Exo-Earth Characterized via Thermal Emission

4.7 µm R ~ 10 S/N = 25 Distance = 1 AU

Temperature	**Integration Time 30m GSMT**	**Contrast Ratio**	**Integration Time 100m OWL**
500 K (Warm Earth) (1.3µJy @ 4.7 µm)	150 hours	$5x10^6$	1 hour
300K (29nJy @ 4.7 µm)	$3x10^5$ hours	$2x10^8$	2500 hours

NB: Calculated times assume NO contribution from parent star



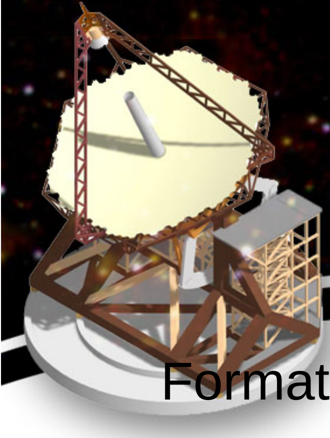
Conclusions

- A 30m GSMT can:
  - Detect; classify; analyze young (t < 100 Myr) EGPs to ~ 30pc
    - Young EGPs more massive than 1 Mj can be seen to TW Hya distance
    - Observations can constrain origin scenarios
  - Detect & classify old EGPs in the solar neighborhood (d < 10pc)
  - Detect earth-radius planets to distances of several pc
    - Star rejections ~ 10^9 needed
  - Exo-earths are marginal for 30 meters, possible for 100 m

3. Gas in the Planet Formation Region of Disks:

Diagnosing Where and When Planets Form During the Accretion Phase

Joan Najita & Steve Strom



How do Planetary Systems Form?

When, Where? How frequently?

Formation and evolution of planetary systems is complex…

grain coagulation
gas accretion
gap formation
orbital migration
dynamical scattering

Mass assembly

Interaction with disk

Inter. with other planets

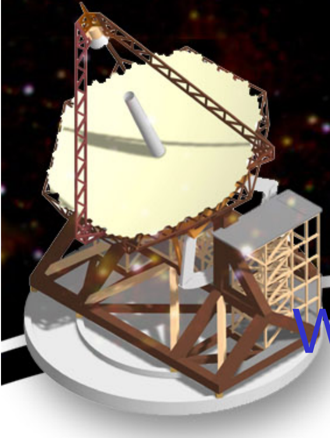
many processes
affect evolution
of planetary
m, a, e

Theory may need help from observations!

Approach: study solar system analogues in the process of formation

To date: outer disks (e.g., millimeter, scattering; > 30 AU)
very inner disks (< 0.2 AU)

Goal: planet formation region at r < 10 AU



Questions &Measurements

When Do Planets Form?

Measure gas dissipation timescale

(constrains giant planet formation timescale)

Look for residual gas in low continuum opacity regions

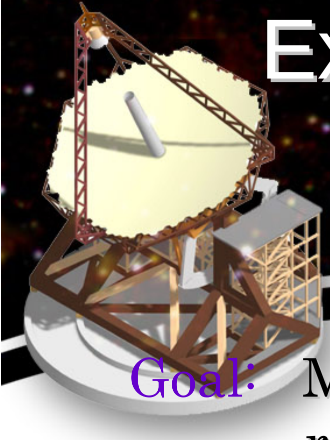
(distinguishes between disk dispersal and grain growth, the first step toward giant and terrestrial planet formation)

Where Do Planets Form?

Difficult to see young planet in the presence of a disk?

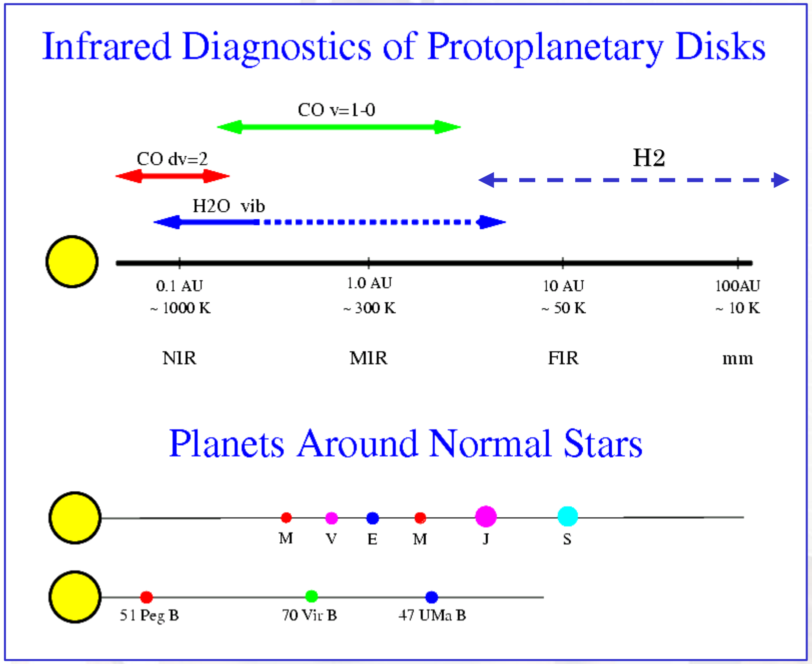
Search for dynamical signatures of planet formation, e.g., gap formation using spectral line diagnostics

(location and width of gap constrains planet orbital radius and mass)



Example GSMT Program: When do planets form?

Goal: Measure disk gas content vs. disk radius in sources over a range in age & environment, esp. dense cluster environment in which the solar system formed.



Infrared Diagnostics of Protoplanetary Disks

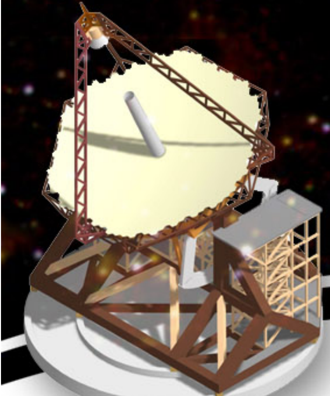
Planets Around Normal Stars

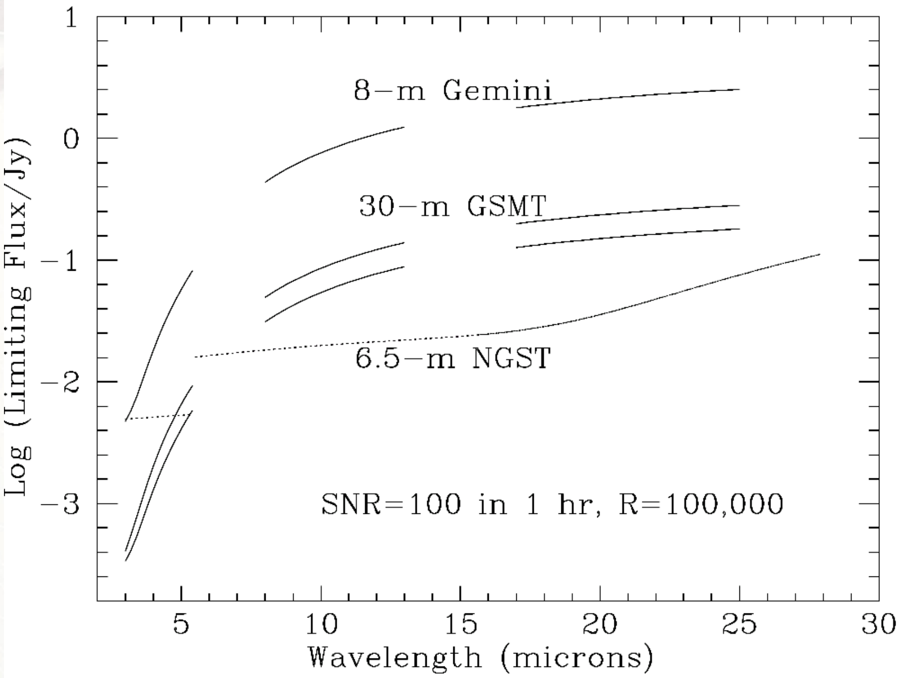
Sensitivity & Distance:

150 pc	sparse associations (Taurus, Cha, Oph)
450 pc	nearest dense cluster (Orion)
1 kpc	other rich clusters

Target CO, H_2O, H_2

Time Requirement





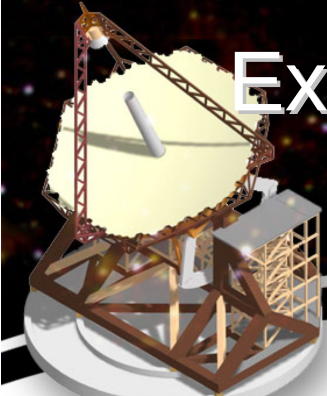
30-m GSMT
10% emissivity

CTTS @ 1 kpc
10μm 9 mJy
20μm 16 mJy

H_2O @ 10μm s/n=25 in 5 hr
H_2 @ 20μm 20 7 hr

15 hr / target for 2 settings
with calibration and overhead

For 30 targets / cluster with a spread in age
5 clusters
= 250 nights



Example GSMT Program: Where do planets form?

Goal: Measure M_p and a_p for a statistically significant sample of protoplanets in systems spread over a range of age and environment.

Sensitivity & Distance:

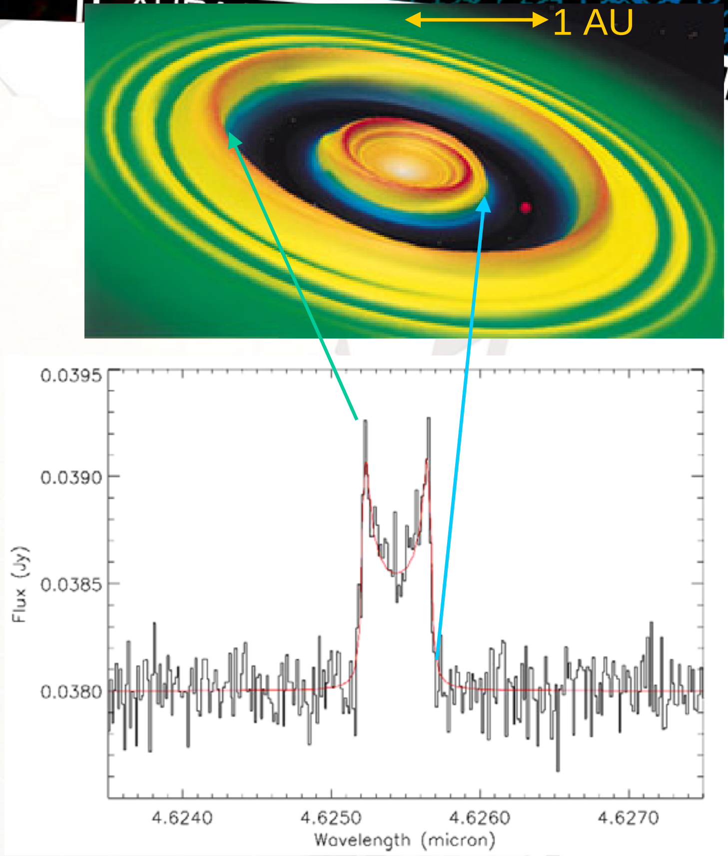
150 pc	sparse associations (Taurus, Cha, Oph)
450 pc	nearest dense cluster (Orion)
1 kpc	other rich clusters

If 5—10% of stars form Jupiters,

→ Recovery of a sample of ~100 protoplanets requires a survey of 1000 T Tauri stars

→ need to reach Orion (480 pc)

Forming Jupiter mass planet at 1AU opens gap 0.3 AU wide.



S/N ~ 300 needed to search for dynamical signature of protoplanet

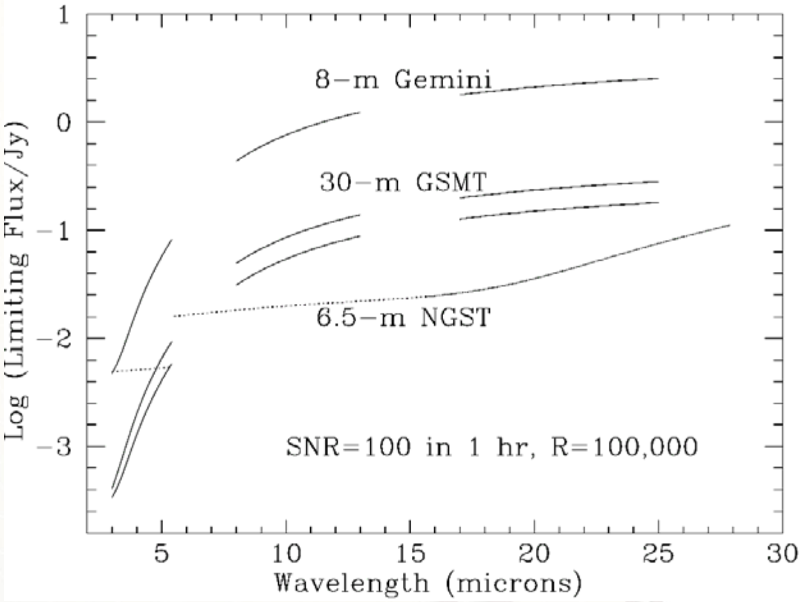
Time Requirement

30-m GSMT
10% emissivity

CTTS at 450 pc (Orion)

4.7µm CO s/n=300 in 15min
45 min / target with overhead and calibration.
→ 1000 targets in 100 nights

10µm H_2O s/n=100 in 4 hr
4.5 hr / target with overhead and calibration
→ 1000 targets in 500 nights

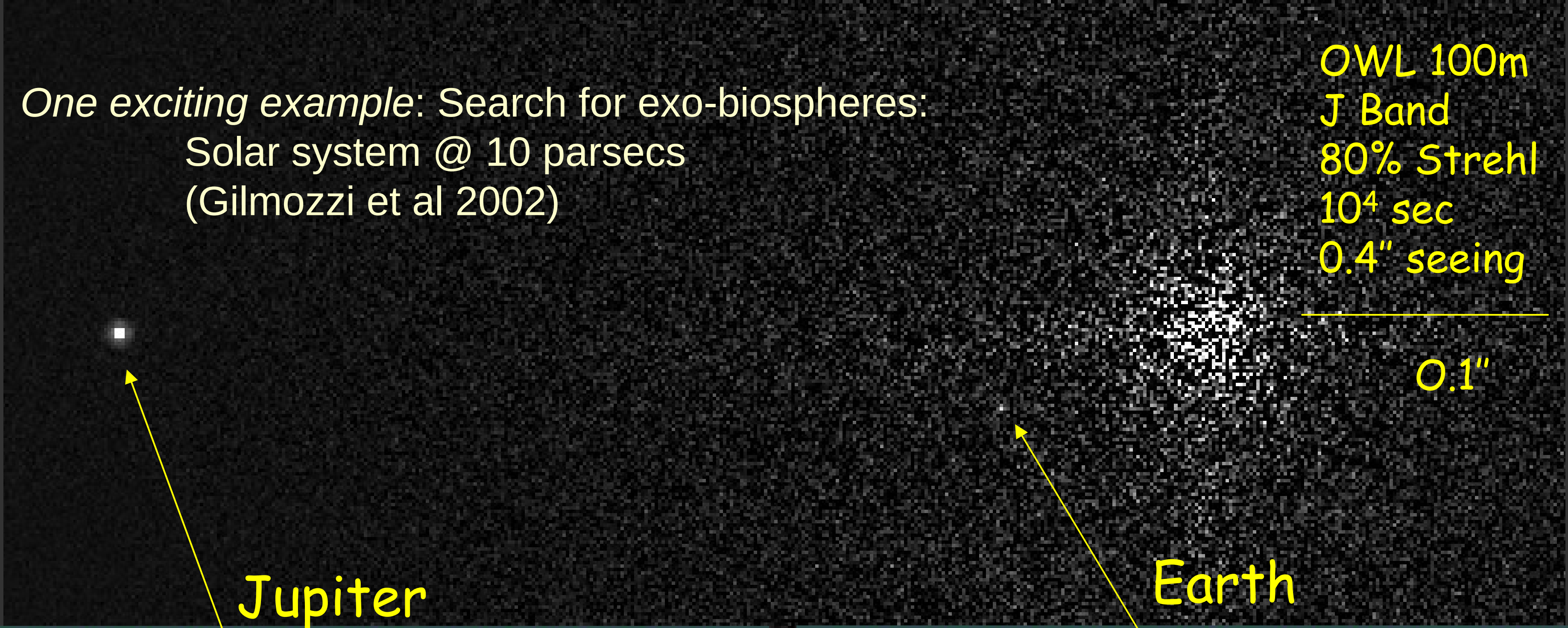


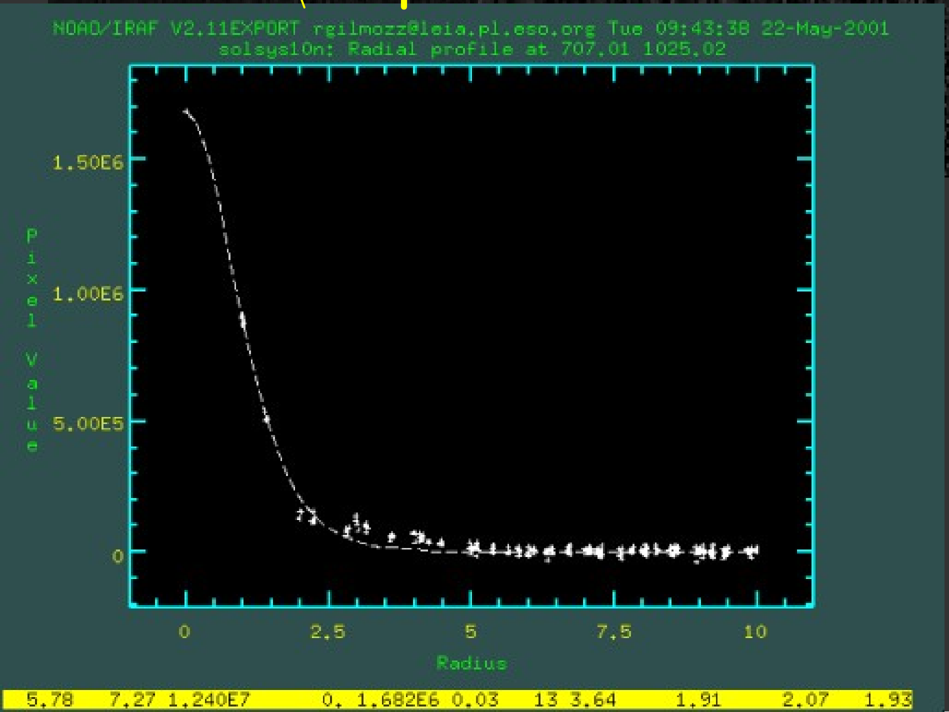
One exciting example: Search for exo-biospheres:

Solar system @ 10 parsecs

(Gilmozzi et al 2002)

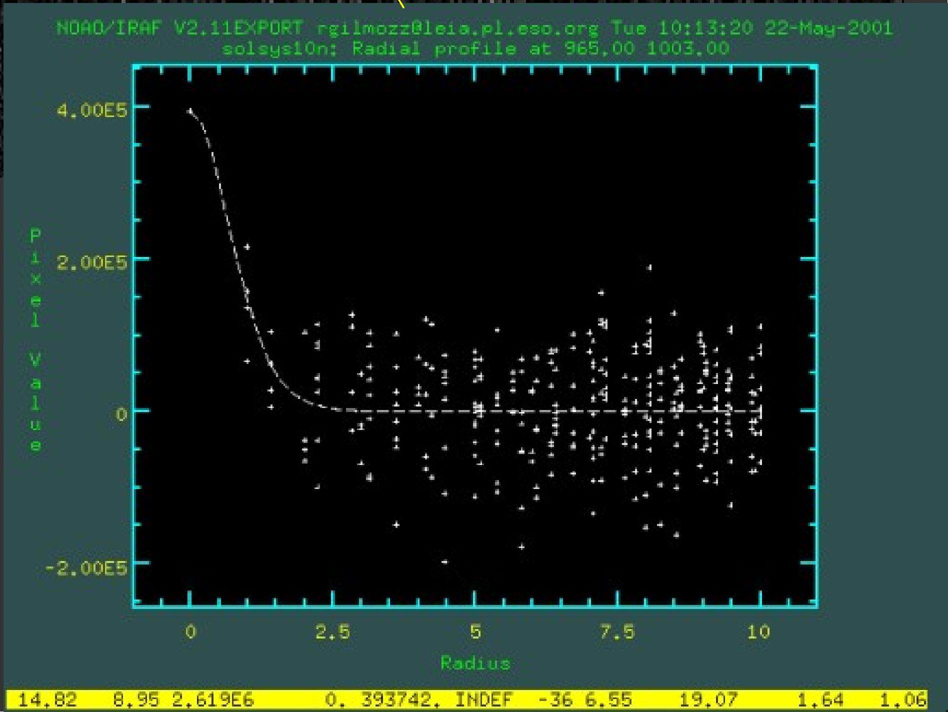
OWL 100m
J Band
80% Strehl
10^4 sec
0.4" seeing





```
NOAO/IRAF V2.11EXPORT rgilmozz@leia.pl.eso.org Tue 09:43:38 22-May-2001
solsys10n: Radial profile at 707.01 1025.02
```

```
5.78   7.27 1.240E7      0. 1.682E6 0.03   13 3.64      1.91      2.07    1.93
```



```
NOAO/IRAF V2.11EXPORT rgilmozz@leia.pl.eso.org Tue 10:13:20 22-May-2001
solsys10n: Radial profile at 965.00 1003.00
```

```
14.82   8.95 2.619E6      0. 393742. INDEF  -36 6.55      19.07      1.64    1.06
```