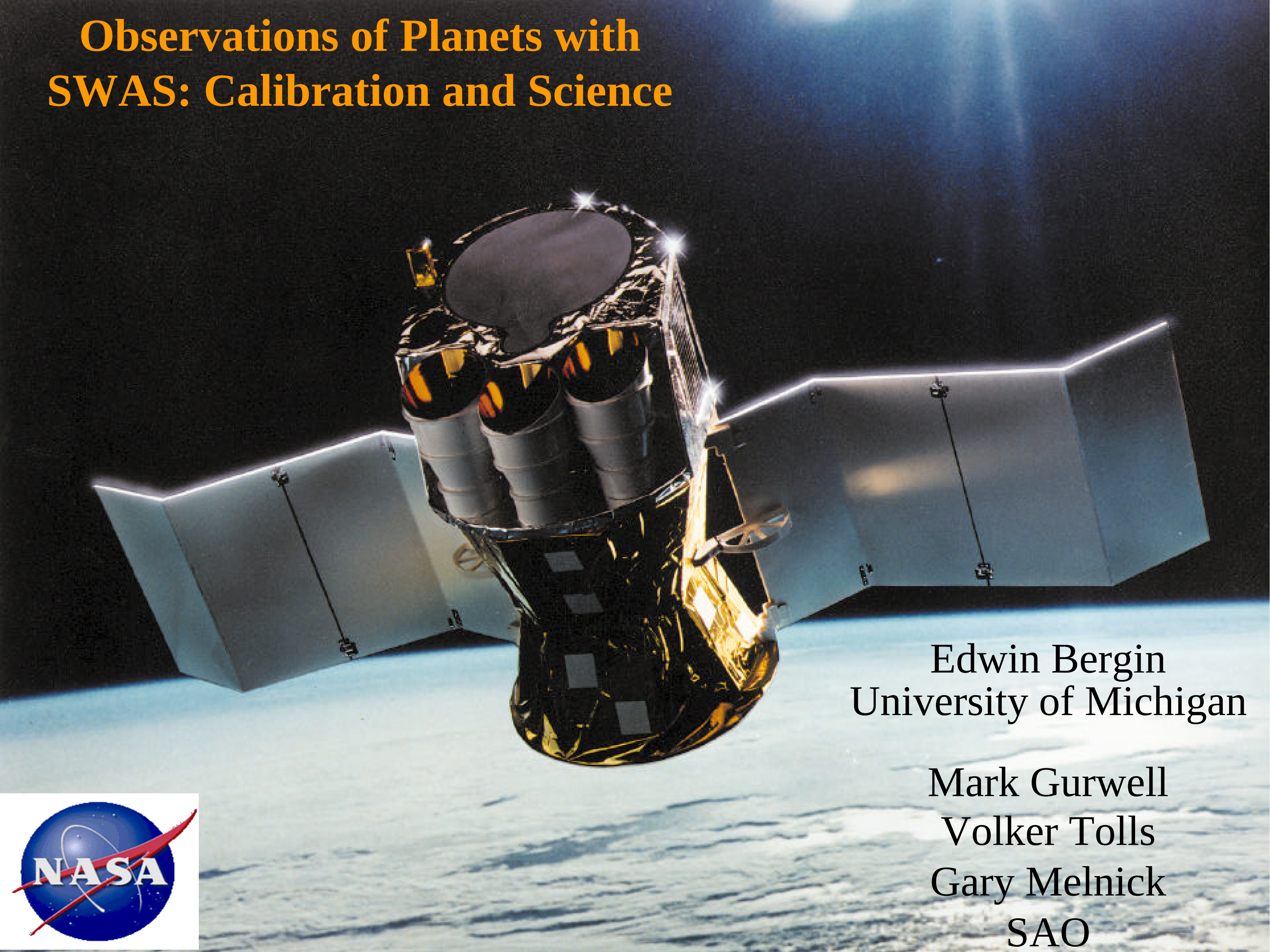
Observations of Planets with SWAS: Calibration and Science



Edwin Bergin
University of Michigan

Mark Gurwell
Volker Tolls
Gary Melnick
SAO

An Explorer for the Submillimeter region

- **SWAS is designed to observe five astrophysically important lines that are either difficult or impossible to observe from within the atmosphere (538 to 615 microns)**

H_2O $H_2{}^{18}O$ O_2 CI ${}^{13}CO$

High spectral resolution ($\lambda/\Delta\lambda \sim 300{,}000 \Leftrightarrow 1$ km s^{-1})
Field-of-View: ~ 4 arcminutes (54 x 68 cm = 3.3' x 4.5' at 557 GHz)
3-axis stabilized pointing: 5" absolute pointing; 3-5" pointing stability

- **First space observatory to carry out pointed observations at submillimeter wavelengths**
- **Dedicated to the spectroscopic study of star formation and interstellar chemistry**
- **Provides our first opportunity to study cold water vapor and molecular oxygen in star-forming interstellar gas clouds**

Melnick et al 2000; Tolls et al 2004

An Explorer for the Submillimeter region

- 54 x 68 cm primary; off axis; 11 dB edge taper
- chopper wheel calibration - all data on T_A^* scale
- observing modes
  - — NOD - primary method of observation
  - — chop - 10’ throw (2 Hz and 1/4 Hz)
  - — dual beam chopping (complications... V. Tolls)
- SWAS is/was a spectroscopic mission and nearly all science was done using AOS
- SWAS did carry a total power continuum detector primarily designed to use Jupiter to find the sub-mm beam -- star tracker offset
  - — was used later for science observations in dual beam chopping mode

Melnick et al 2000; Tolls et al 2004

SWAS: Observed Molecules and Transitions

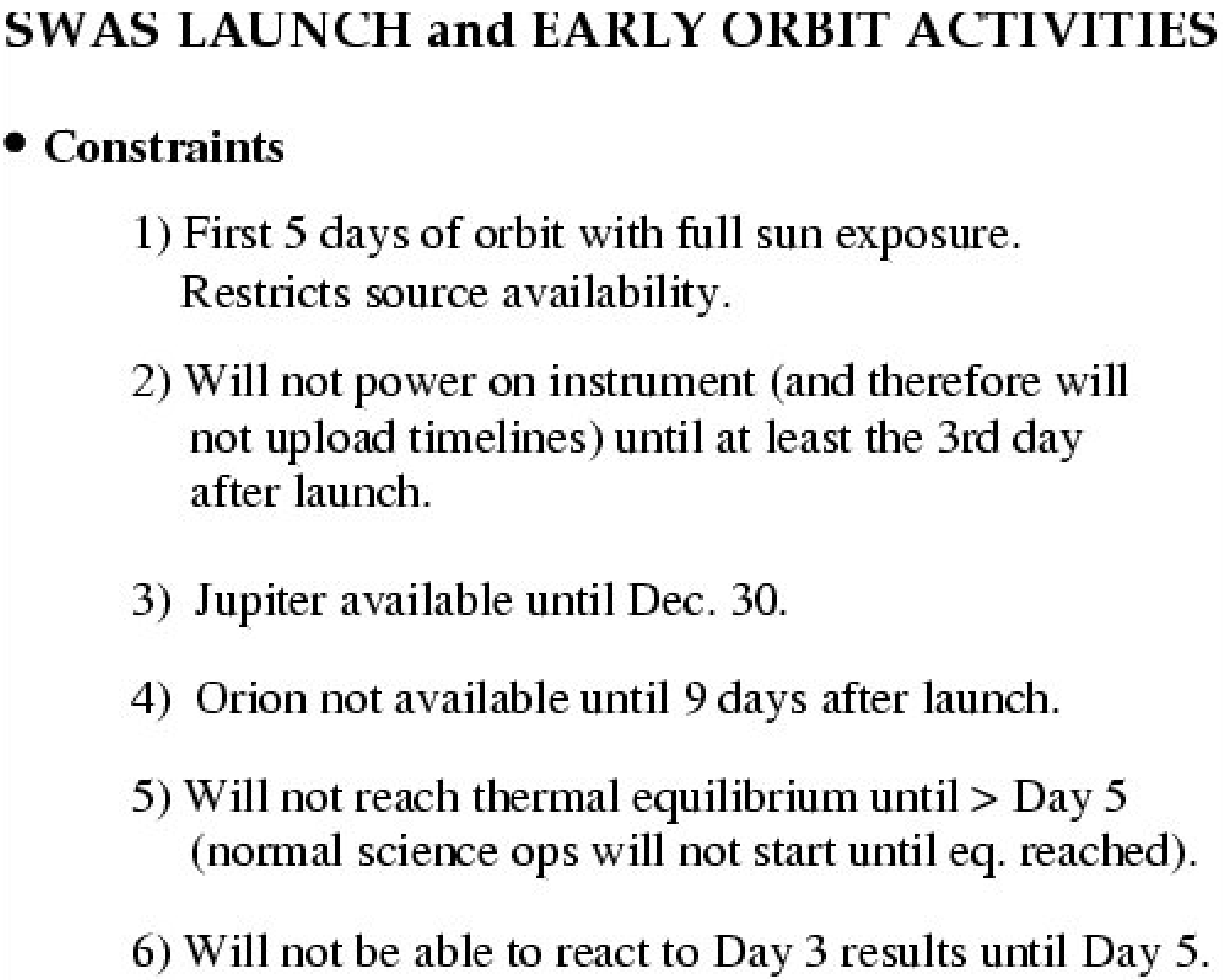
Species	Transition	Energy Above Ground State (E/k)	Frequency (GHz)	Wavelength (μm)	Critical Density (cm^{-3})
O_2	$3,3 \rightarrow 1,2$	26 K	487.249	615.276	10^3
CI	$^3P_1 \rightarrow {}^3P_0$	24 K	492.161	609.134	10^4
$H_2{}^{18}O$	$1_{10} \rightarrow 1_{01}$	26 K	547.676	547.390	10^9
^{13}CO	$J = 5 \rightarrow 4$	79 K	550.926	544.161	3×10^5
H_2O	$1_{10} \rightarrow 1_{01}$	27 K	556.936	538.289	10^9

Transitions listed in red are ground-state transitions.

SWAS Initial Calibration

- SWAS launch: Dec. 5, 1998
- Mars was used the primary calibrator
  - giant planets were not well characterized in the sub-mm.
  - Mars was not available for observations until April 1999.
  - Used ground-based line observations of neutral carbon for initial calibration checks (Rene Plume's focal reducer on the CSO) - this later provided confirmation of planetary calibration results.
- First "calibration" activity on-orbit was to find the sub-mm beam offset relative to the star tracker pointing.

SWAS Initial Calibration



SWAS LAUNCH and EARLY ORBIT ACTIVITIES

- **Constraints**

1) First 5 days of orbit with full sun exposure. Restricts source availability.

2) Will not power on instrument (and therefore will not upload timelines) until at least the 3rd day after launch.

3) Jupiter available until Dec. 30.

4) Orion not available until 9 days after launch.

5) Will not reach thermal equilibrium until > Day 5 (normal science ops will not start until eq. reached).

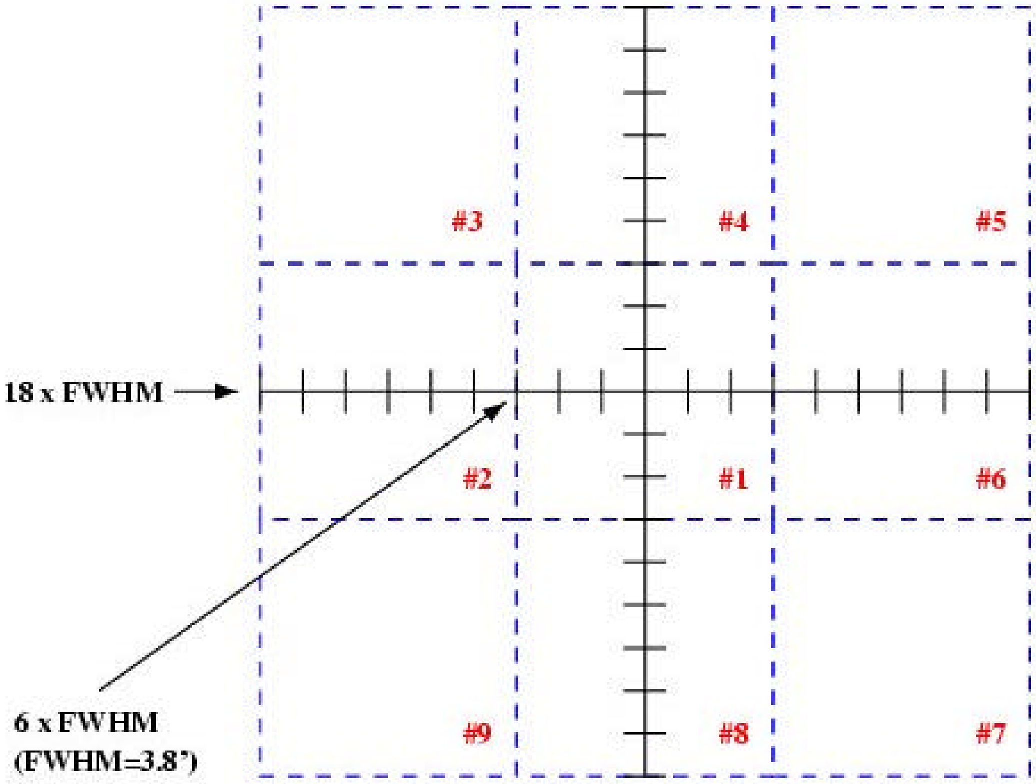
6) Will not be able to react to Day 3 results until Day 5.

Actually had a 3-5 hour turn-around time

SWAS Initial Calibration: Beam Finding

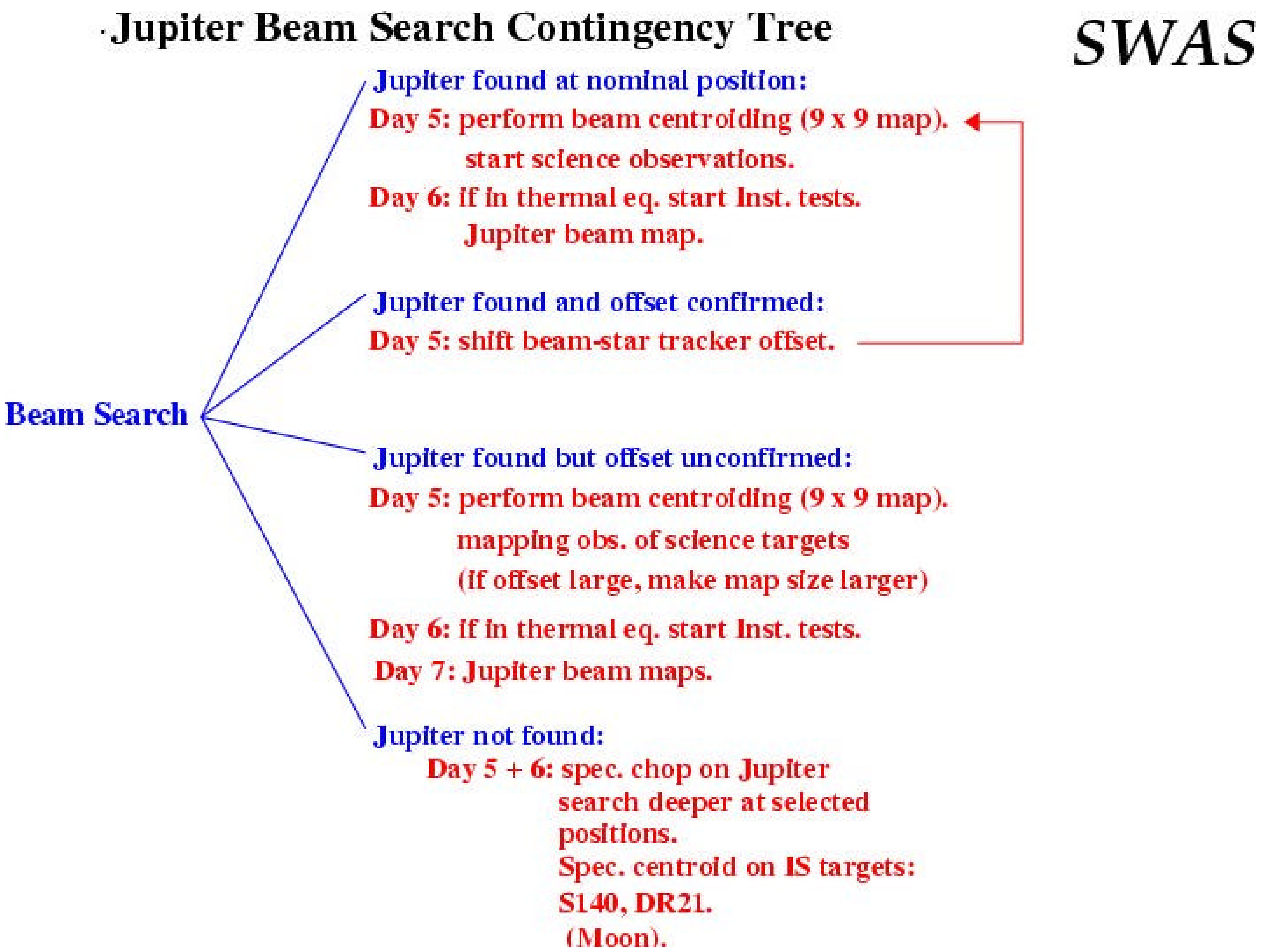
Jupiter Beam Search - Day 3

Area: 2.3 deg. by 2.3 deg.



SWAS

SWAS Initial Calibration: Beam Finding



Jupiter Beam Search Contingency Tree

SWAS

Beam Search

Jupiter found at nominal position:

Day 5: perform beam centroiding (9 x 9 map).
start science observations.
Day 6: if in thermal eq. start Inst. tests.
Jupiter beam map.

Jupiter found and offset confirmed:

Day 5: shift beam-star tracker offset.

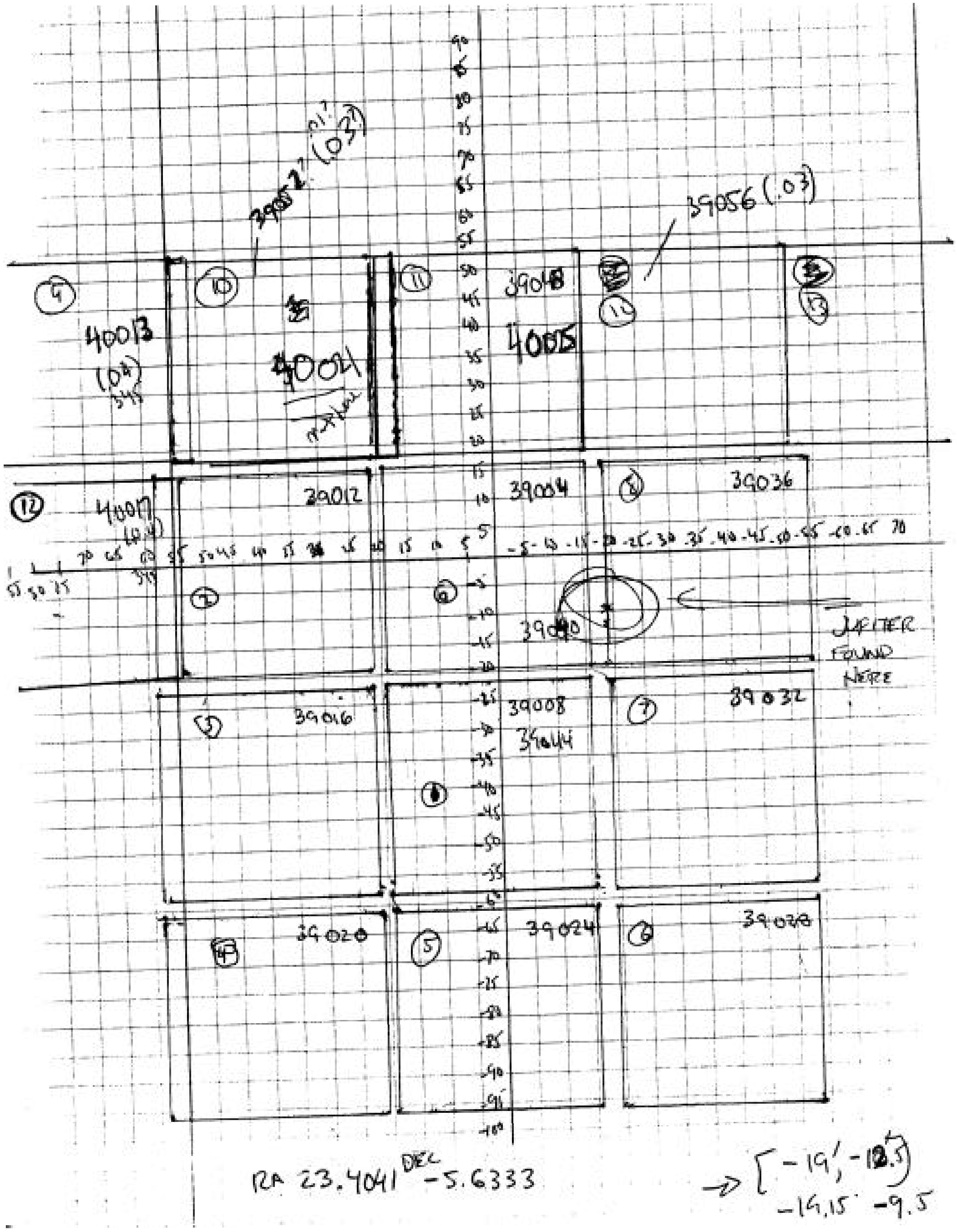
Jupiter found but offset unconfirmed:

Day 5: perform beam centroiding (9 x 9 map).
mapping obs. of science targets
(if offset large, make map size larger)
Day 6: if in thermal eq. start Inst. tests.
Day 7: Jupiter beam maps.

Jupiter not found:

Day 5 + 6: spec. chop on Jupiter
search deeper at selected positions.
Spec. centroid on IS targets:
S140, DR21.
(Moon).

SWAS Initial Calibration: Beam Finding



SWAS Initial Calibration: Flux

- Mars observed continuously on:
  - 4/17/99 - 5/2/99 (epoch 1)
  - 6/5/99 - 6/9/99 (epoch 2)
  - θ = 15.6” to 16.2”
- Martian season was L_s ~ 130 (mid-northern summer).
- Spectra collected over a series of 30 minute observations (called segments). Consists of over 200 segments (> 1800 minutes) in total.
- For calibration used the Rudy thermal model of Martian surface and sub-surface.
  - initially used to calibrated cm wavelength observations
  - extended into mm (M. Gurwell and others)

SWAS Initial Calibration: Flux

- 2 channels
  1. C I/O_2 (490 GHz)
  2. H_2O/^{13}CO (553 GHz)
- In channel 2 the water line exceeds the width of the bandpass (350 MHz)
  - cannot get a measurement of continuum level
- Initial calibration was done on channel 1 and this value was used to estimate the efficiency of channel 2.
  - Ch. 2 efficiency later confirmed by scans of the Moon and by observations of $H_2{}^{18}O$ in ch. 2 when Mars was larger.
- Observed flux in ch. 1 was 1.0 ± 0.05 K (DSB)

SWAS Initial Calibration: Flux

- Some equations:

$$T_A^* = \frac{e_A A_p S_{Mars}}{2k}$$

ε_A = aperture efficiency
A_p = physical area of antenna

$$S_M = \frac{2kT_{RJ}}{l^2}\Omega_{Mars}$$

S_M = flux from Mars
T_{RJ} = Rayleigh-Jeans corrected brightness temperature from model

SWAS Initial Calibration: Flux

- For Mars T_{RJ} and Ω_{Mars} will vary with time
- SWAS has data over 2 epochs but T_{RJ} was roughly constant within each epoch
- Ratio of S_M / Ω_M will be nearly constant within each epoch - so:

$$\frac{S_M}{\Omega_M} = \frac{1}{e_A}\left\langle \frac{2kT_A^*}{A_p\Omega_M} \right\rangle$$

$$e_A = \frac{l^2}{2k\left\langle T_{RJ} \right\rangle}\left\langle \frac{2kT_A^*}{A_p\Omega_M} \right\rangle$$

Values in brackets are time-weighted averages.

$$e_{MB} = \frac{\Omega_{MB}}{\Omega_A} = \frac{\Omega_{MB}}{l^2 / e_A A_p}$$

ε_{MB} = main beam efficiency

Ω_{MB} = main beam solid angle

SWAS Initial Calibration: Flux

Complications

- Epoch 1:
  - Mars was not properly centered during the observations (offset by 0.15’,0.67’)
  - Mars was nearing opposition and was drifting with the beam at a rate of 0.91’/hour.
  - Effects of parallax were not accounted for in the timelines
- Epoch 2:
  - Mars centered
  - Effects of parallax not corrected, but segments were shorter and effect is smaller (< 1%)
  - Motion of Mars 0.13’ per hour
  - Observation time (~11 hours) significantly less than Epoch 1 (~33 hours)

SWAS Initial Calibration: Flux

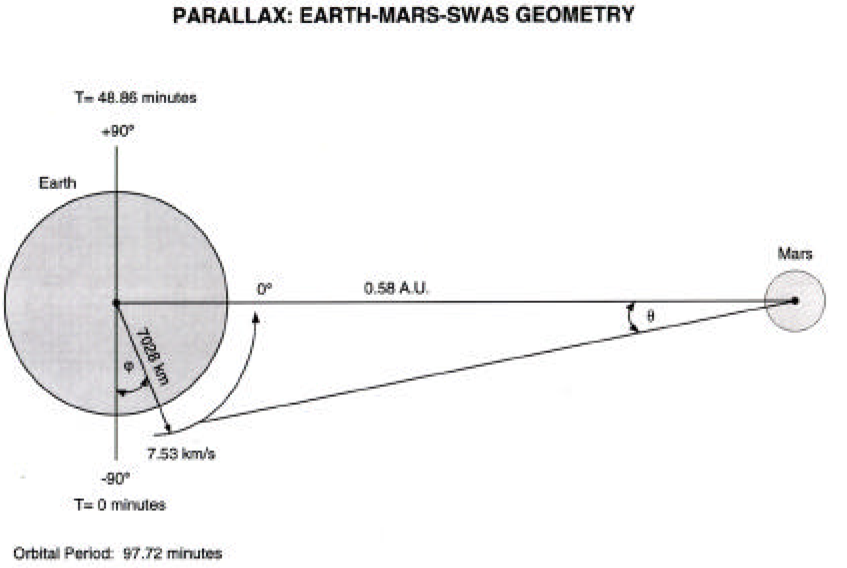


Fig. 1

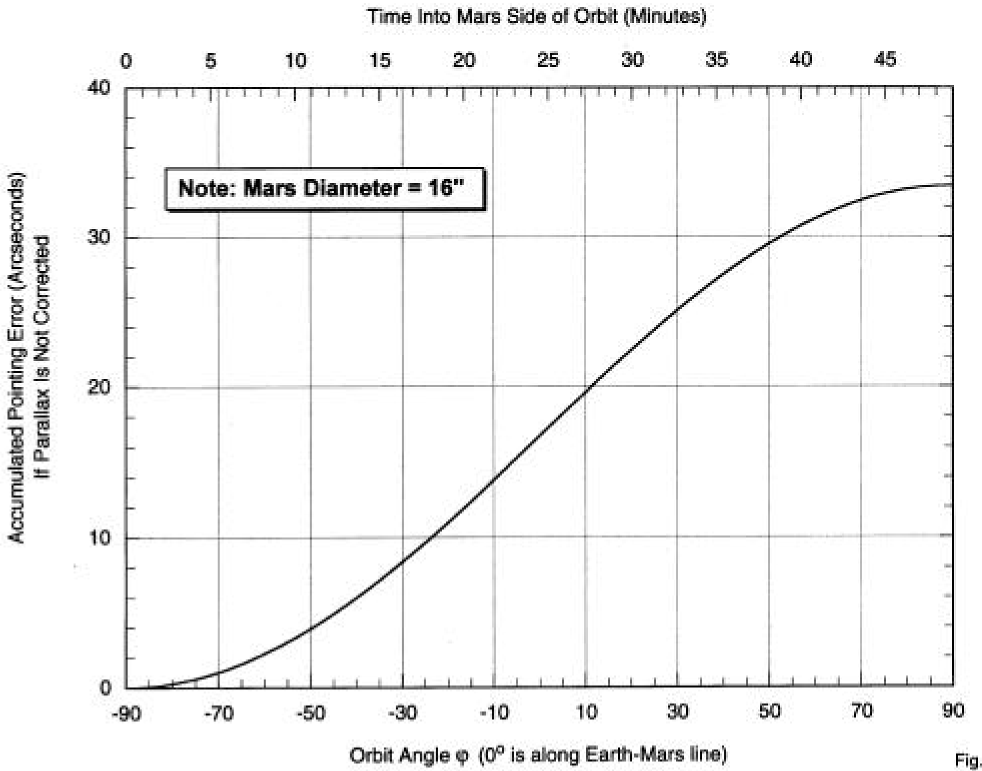


Fig.

SWAS Initial Calibration: Flux

Complications

- Epoch 1:
  - Mars was not properly centered during the observations (offset by 0.15',0.67')
  - Mars was nearing opposition and was drifting with the beam at a rate of 0.91'/hour.
  - Effects of parallax were not accounted for in the timelines
- Epoch 2:
  - Mars centered
  - Effects of parallax not corrected, but segments were shorter and effect is smaller (< 1%)
  - Motion of Mars 0.13' per hour
  - Observation time (~11 hours) significantly less than Epoch 1 (~33 hours)

Cumulative effect of errors varies but at maximum was 5% (mostly due to pointing error which could be corrected).

SWAS Initial Calibration: Flux

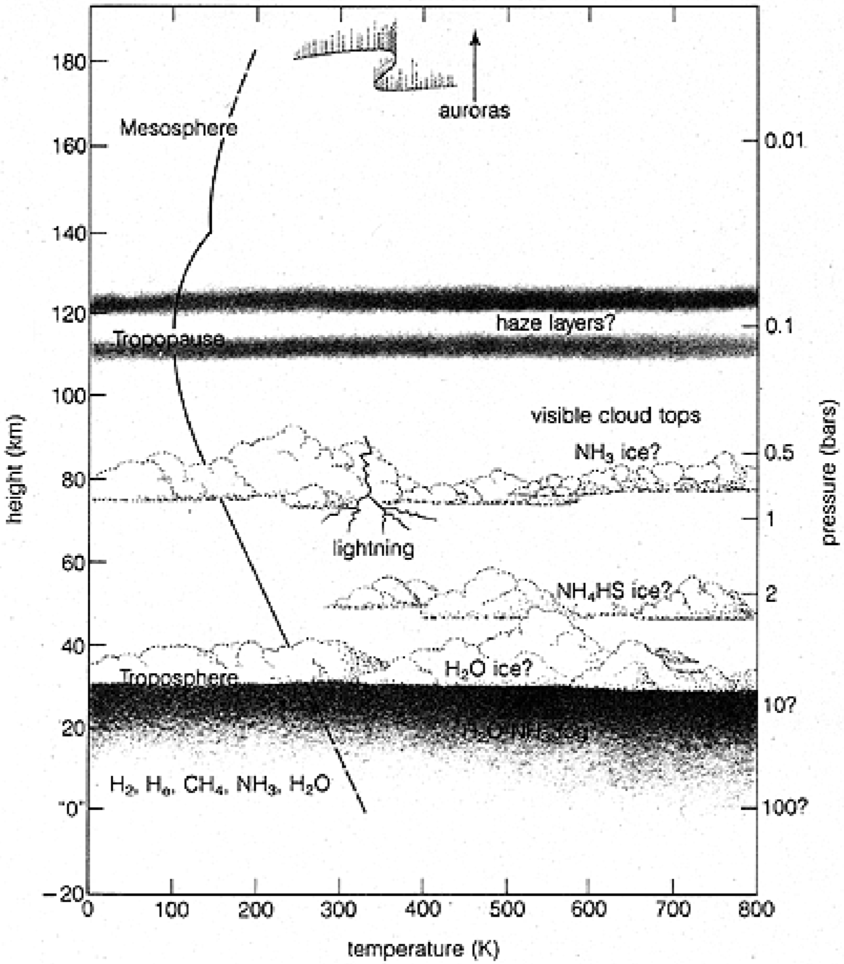
	Epoch 1	Epoch 2	All Data	Preferred Value
ε_A	65±3%	70 ±3%	66 ±3%	66%
ε_M	93 ±7%	100 ±7%	94 ±7%	90%

- Adopted 90% main beam efficiency as it is maximum theoretical limit for a filled antenna with an unblocked aperture with an 11dB edge taper is 90%
- Ch. 2 efficiency assumed to be similar (Ruze formula for 18 µm surface rms suggests efficiency is 4% lower - consistent with later results).

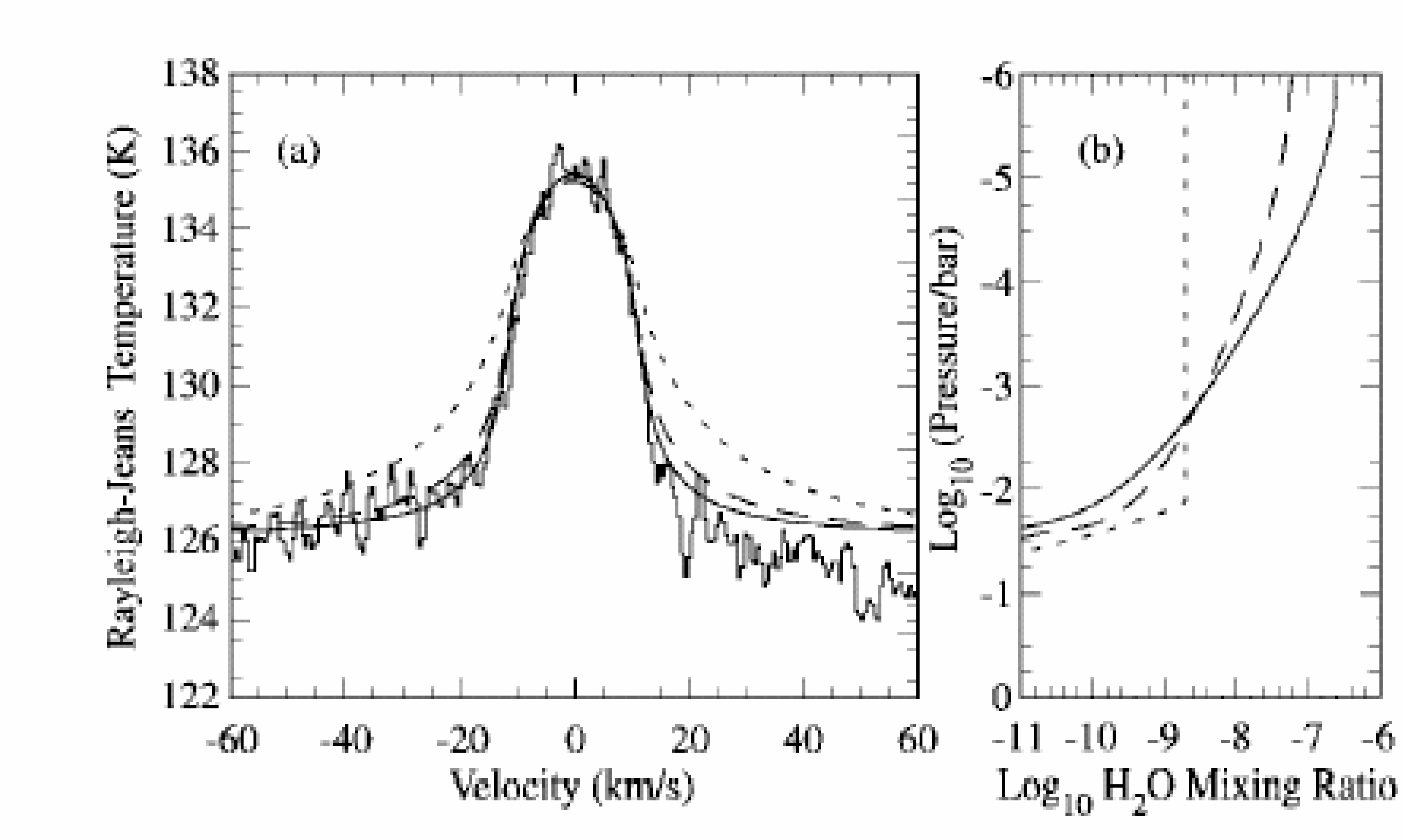
Jupiter and Saturn

- Tropospheric water vapor from deep atmosphere known for many years.
  - Galileo NMS detected H_2O at ~ 4 - 8 bar (Roos-Serote et al. 1998).
  - Galileo probe mass spectrometer measured H_2O abundance at > 11 bar (Niemann et al. 1998).
- ISO detected H_2O in stratosphere of all four giant planets and Titan: likely derived from impact of micrometeorites and SL9 for Jupiter (Feuchtgruber; Lellouch).

⇒ The high spectral resolution of SWAS permitted retrieval of the vertical profile of water, an important test of impact theory.



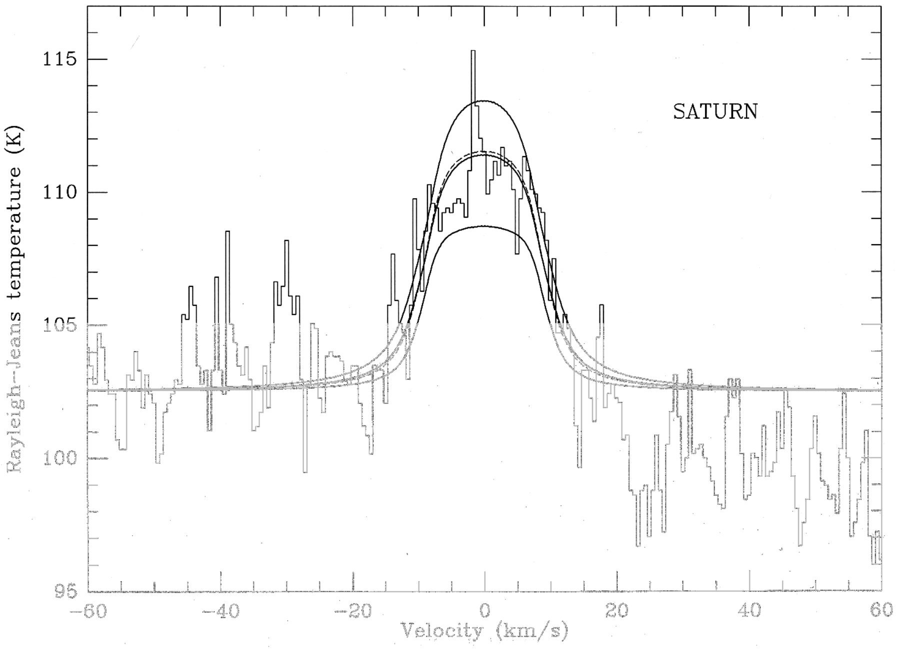
Stratospheric Water on Jupiter

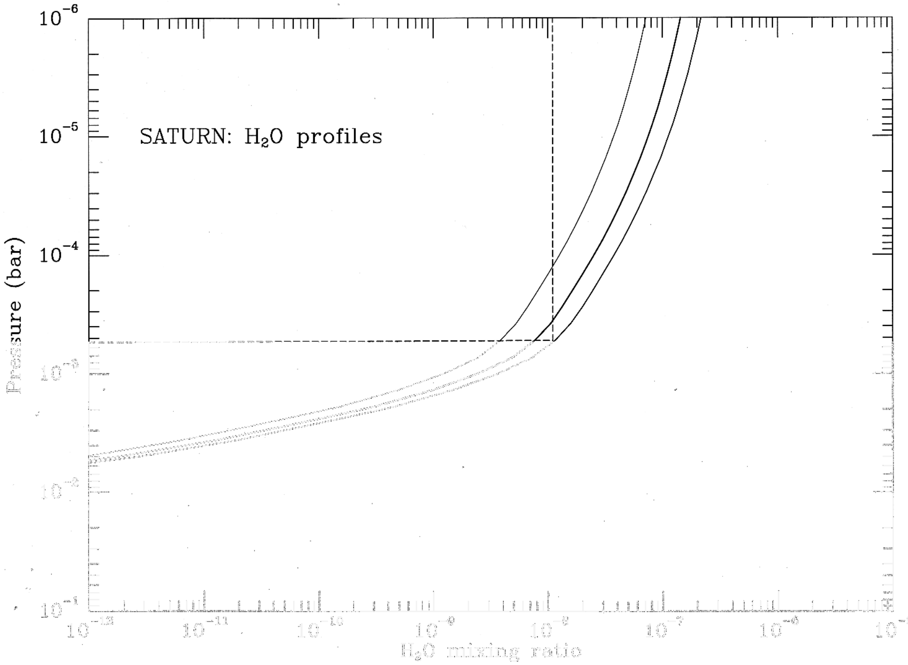


- Best fit to spectrum obtained with non-uniform water vapor profile, increasing with altitude.
- Consistent with external source model.
- Column density = 2.8×10^{15} cm^{-2}; ~1.7 times ISO results (Lellouch et al. 1997).

Bergin et al 2000; Lellouch et al 2002

Stratospheric Water on Saturn

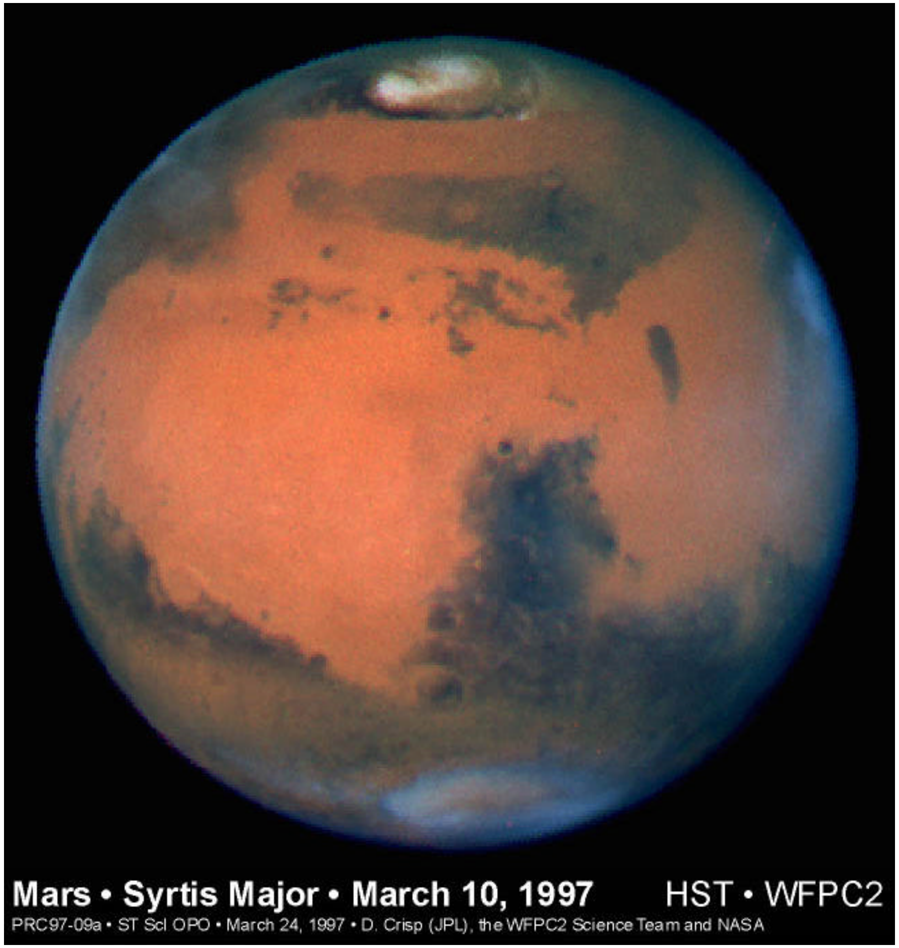




- Spectrum well fit by either constant water vapor profile or with profile increasing with altitude.
- Does show effect of condensation.
- Column density = 1.9-5.4 × 10^{15} cm^{-2}; ~2 times ISO results (Moses et al. 2000).
- Analysis suggests rings contribute 29% of flux (depends on viewing angle)

Bergin et al 2000

Mars

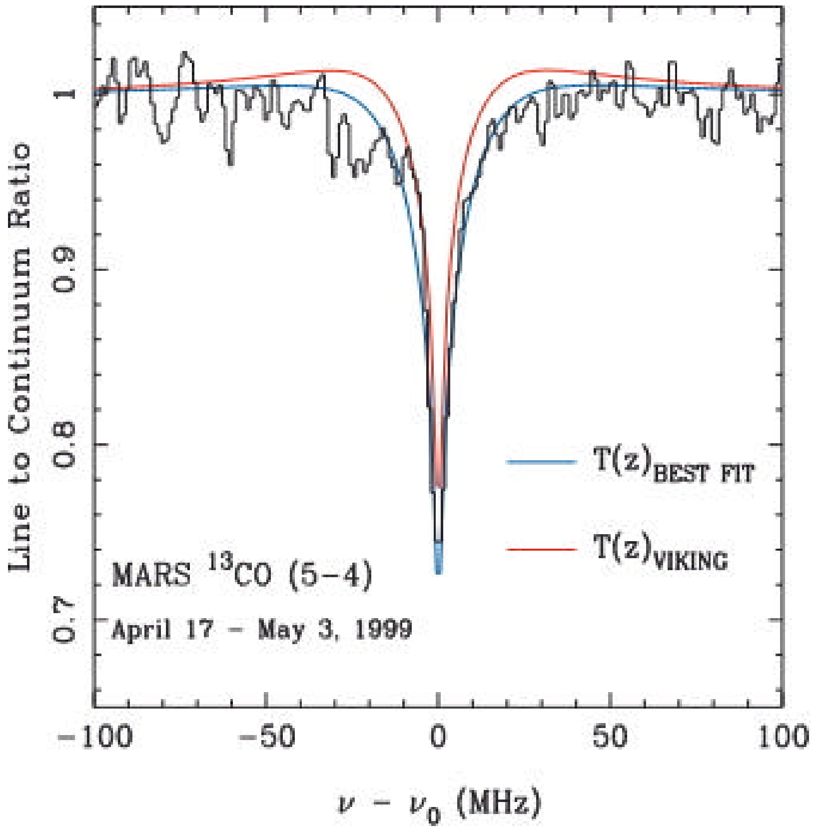


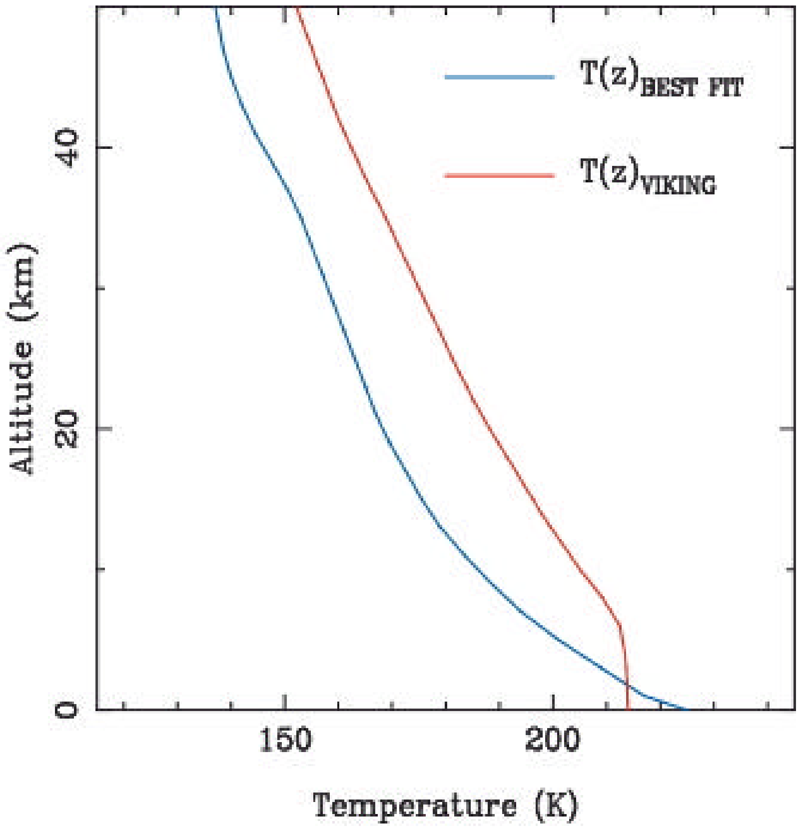
- Primary calibration source
- Variable atmospheric temperature profile
- Highly variable water column and profile

⇒ 1999: SWAS measured both the atmospheric temperature and water vapor vertical profiles

⇒ 2001: SWAS measured atmospheric temperature profile during global dust storm

Mars 1999: ^{13}CO and Temperature

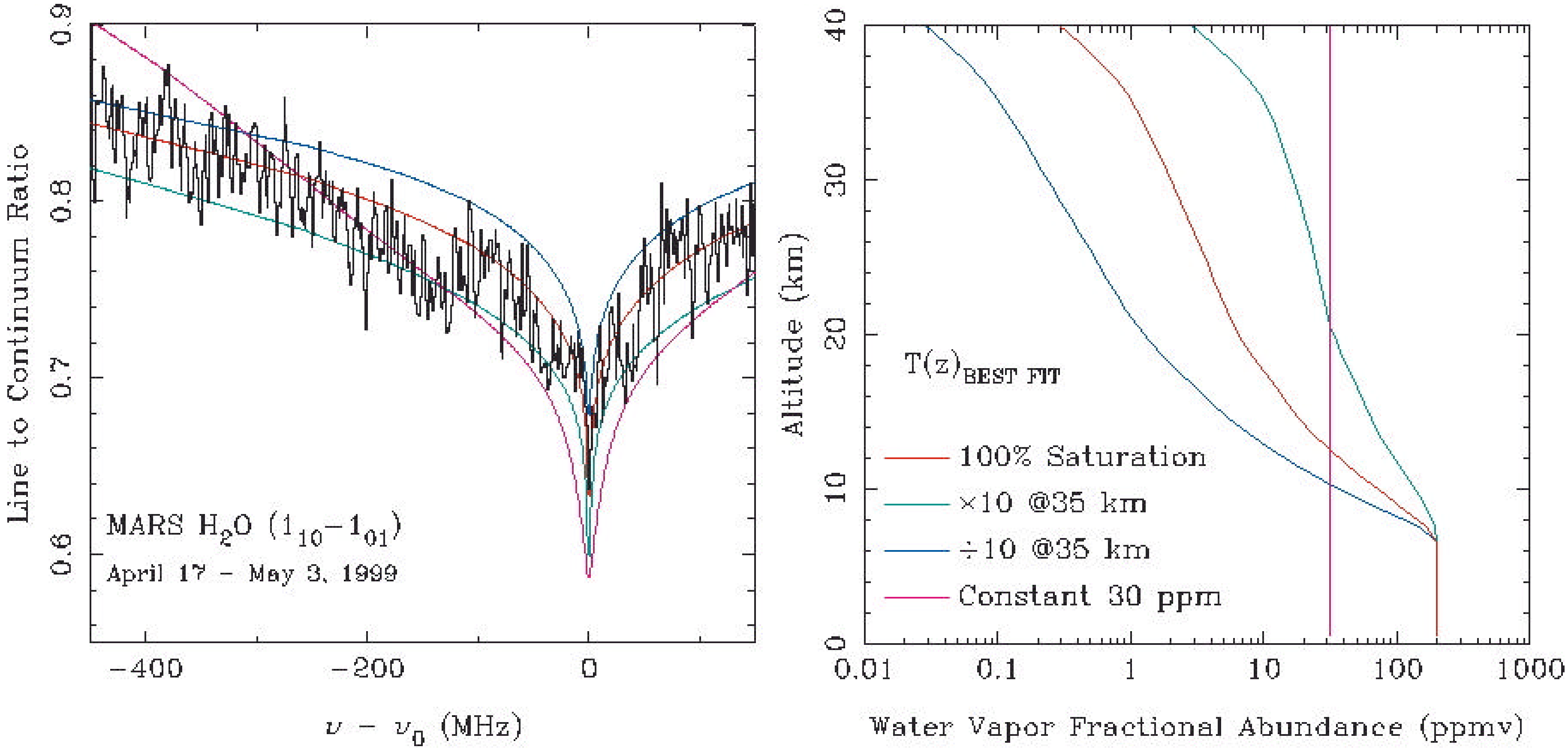




- Martian atmosphere ~20 K cooler than during Viking era (e.g. Zurek et al. 1992).
- Verifies cold temperatures found through mm spectroscopy (Clancy et al. 1996).

Gurwell et al 2000

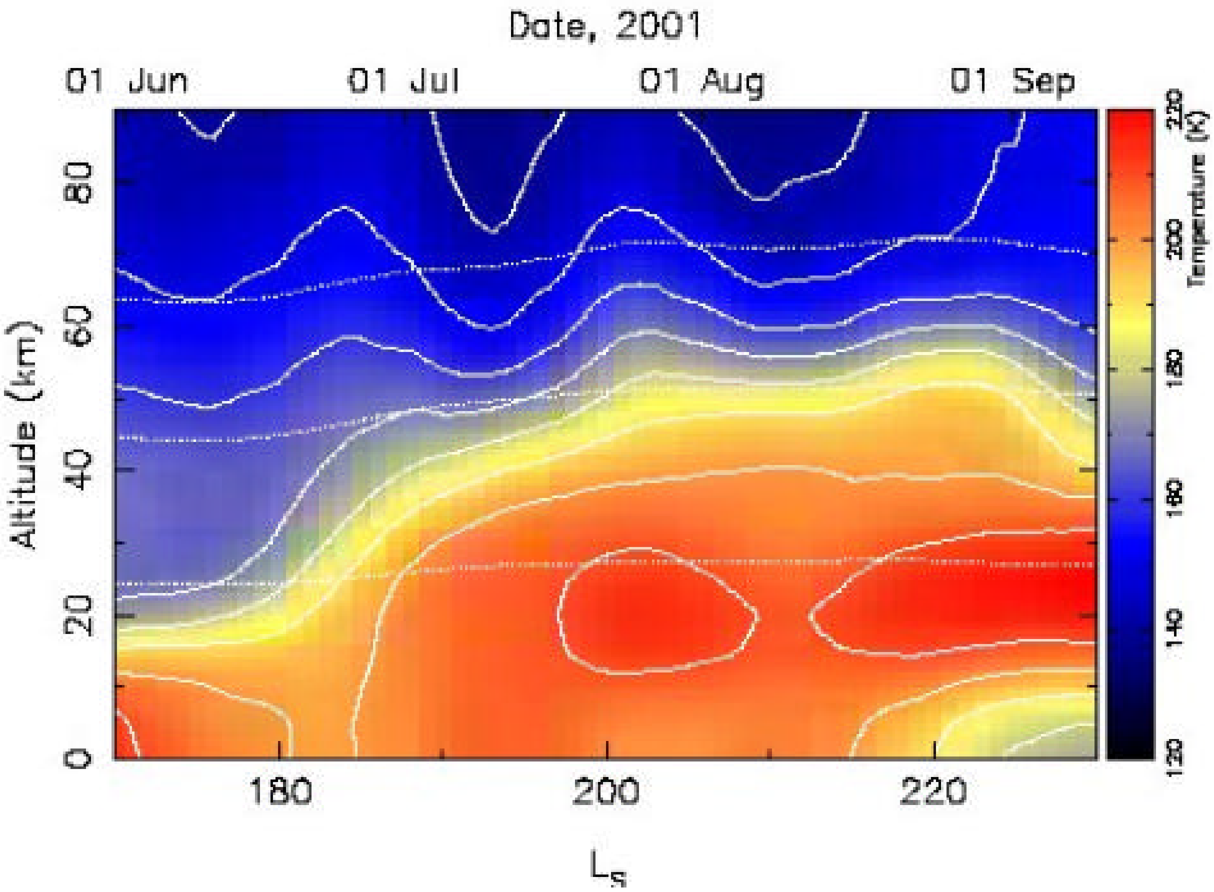
Mars 1999: Water Vapor Profile

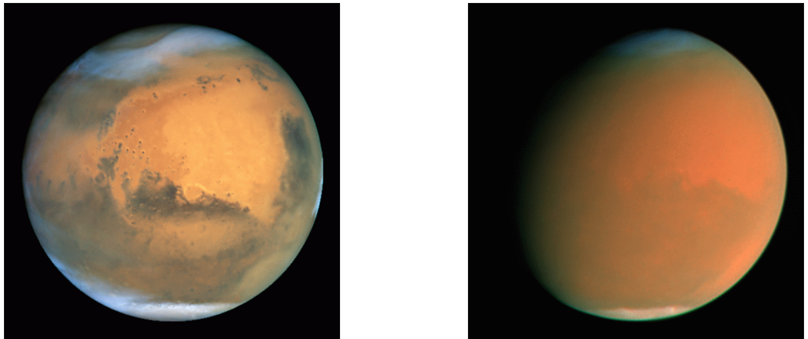


- Cold temperatures imply low saturation altitude ~ 7 km; nominal 8 pr micron.
- Best fit by water vapor profile with 100% saturation above 7 km.

Gurwell et al 2000

Mars 2001: Temperature Profile and Global Dust Storm

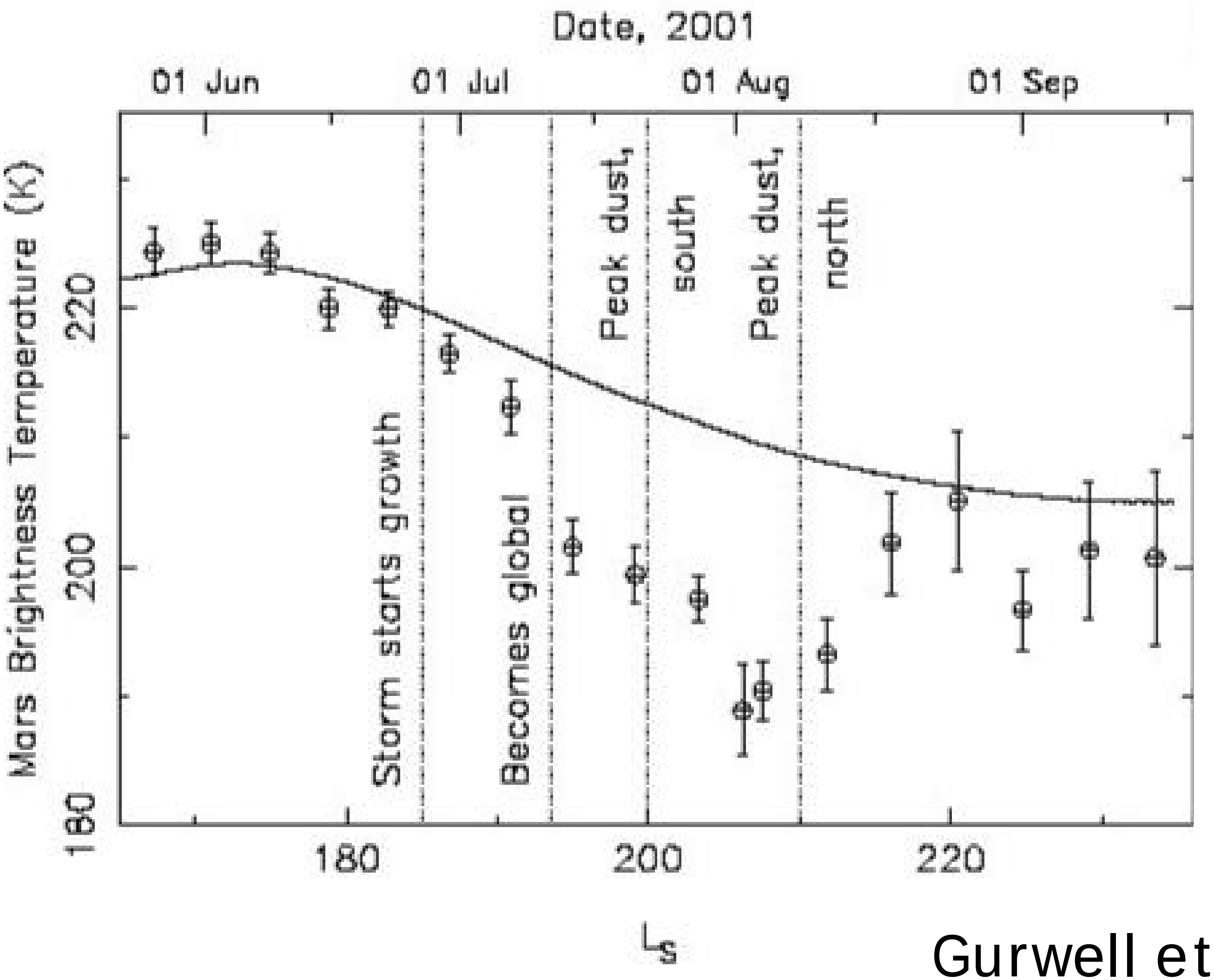




- SWAS measurements of the ^{13}CO(5-4) and $H_2O(1_{10}-1_{01})$ rotational transitions allowed retrieval of the temperature profile from the surface to 90 km.
- The global dust storm raised atmospheric temp by up to 40 K above pre-storm levels at altitudes of 5-40 km.
- SWAS was the only instrument able to characterize the upper atmosphere of Mars during the storm.

Gurwell et al. 2004

Mars 2001: Surface Temperature and Global Dust Storm



Gurwell et al. 2004

Conclusions

- For calibration:
  - Large wavelength coverage will aid by finding areas free of line emission (use of Uranus as well).
  - Closer planets: movement should be recognized in commanding.
  - Cross-calibration between Herschel instruments will be important.
- For science:
  - Short/Long term monitoring of planets (e.g. Mars) may be difficult because of overhead price (slew, etc.)
  - But… science return can provide information that even observatories orbiting planet (Mars) cannot.
  - Some thought should be placed on how often planets can be re-observed for (cross)calibration checks and science.