MILLIMETER AND SUBMILLIMETER SPECTROSCOPY OF TITAN

Grant NAG5-7946

Final Report

For the period 1 January 1999 through 31 March 2003

Principal Investigator

Dr. Mark A Gurwell

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Final Report
"Millimeter and Submillimeter Spectroscopy of Titan" (NAG5-7946)
P.I.: Mark A. Gurwell

We are pleased to report here the major accomplishments achieved during the execution of our project to study the atmosphere of Titan, funded through NASA Planetary Astronomy Grant NAG5-7946.

Accomplishments: Year 1

Our major goals for the first year of this program were to develop a general improved radiative transfer model of the atmosphere of Titan, and to accurately determine the global abundance of CO from observations obtained using the Owens Valley Radio Observatory Millimeter Array. Other goals were to reanalyze older data sets using the improved radiative transfer model and to observe other molecular species as time permitted.

A) Radiative Transfer Model Development

We have developed a comprehensive line-by-line radiative transfer model of the Titan atmosphere for use at centimeter through submillimeter wavelengths, the Titan Line Model. The model includes rotational lines for 15 species and isotopic variants (CO, HCN, HC_3N, CH_3CN, CH_3C_2H, CH_3OH, C_3H_2, H_2O, CH_3D, ^{13}CO, $C^{17}O$, $C^{18}O$, DCN, $H^{13}CN$, and $HC^{15}N$), with over 12000 individual transitions modeled, as well as induced dipole absorption by molecular nitrogen and methane. The abundance profile for each species and the temperature profile can all be specified independently to an altitude of 750 km (including uncertainties in isotopic ratios), and several formalisms for saturation vapor pressures of certain species are included. Results of one run using nominal inputs are shown in Figure 1. This run extended from 0 to 1000 GHz and calculations were performed at over 300,000 frequencies. The full Voigt lineshape is used for all calculations, and a large literature search was conducted to find the most accurate data on pressure broadening coefficients for each species, if available.

The Titan Line Model is useful for direct comparison with observations, but is most effective as a predictive model, for calculating the possible frequencies and intensities of transitions that can be observed. The Titan Line Model was used to locate the interesting spectral bands we have successfully proposed to observe with the VLA and OVRO interferometers (next section).

B) Interferometric Observations of Spectral Lines

Our Titan program ultimately seeks to spatially resolve Titan's disk in order to measure variations of species abundances and temperature with (primarily) latitude. Earlier this year we answered the Call for Proposals for two facilities with observational proposals related to our Titan program, and each was granted time.

• 1. Search for C_3H_2 with the Very Large Array:

Our first observations will be obtained with the VLA, with which we will attempt to detect the organic radical cyclopropenylidene (C_3H_2), which is created through photodissociation of methylacetylene (CH_3C_2H) in the upper atmosphere of Titan. Both species are important components of the C_3 hydrocarbon photochemical scheme (see Yung et al. 1984). C_3H_2 has never been detected, but recent photochemical models (such as Toublanc et al. 1995) coupled with results from the Titan Line Model suggest that it could be observable with the VLA. Accurate measurements of the abundance and spatial distribution of C_3H_2 will be an important constraint for modeling the chemistry of hydrocarbons in the atmosphere of Titan. Our VLA observations will be at 7mm, and will have a spatial resolution of $\sim 0.15''$ when Titan is $0.85''$, easily allowing spatial variations to be detected if they exist. In addition, the "continuum" emission from Titan will be used to measure latitudinal variations in temperature near the tropopause. These observations will include 3 transit observations of Titan (for a total of 18 hours), and are scheduled for November 28-December 1, 1999.

• 2. Intensive 1mm Spectral Line Observations of Titan with the Owens Valley Radio Observatory Millimeter Array :

We successfully proposed a comprehensive program of observations with the OVRO MM Array to study the vertical abundances of HC_3N, CH_3CN, CH_3C_2H, C_3H_2, and CO in the atmosphere of Titan through careful measurement of the pressure broadened lineshapes of these species. The spectral bands and spectrometer setups were determined through detailed modeling of the expected lineshapes using the Titan Line Model (see section A above). We will resolve Titan with a $\sim 0.4''$ synthesized beam in all spectral lines (except CO, where no variation is expected) in order to search for spatial variations in their abundance profiles. Radiative transfer modeling shows that all species save CO can be observed in a relatively small spectral window, as shown in Figures 2 and 3.

These observations of organics and nitriles will have important consequences for understanding the chemical behavior of the atmosphere of Titan. The observations of CO will help to finally settle the question of the vertical distribution of CO on Titan, which has been the subject of controversy for more than a decade now. We have been granted four tracks for this program, two for the spatially resolved observations of organics and nitriles (scheduled as weather permits during November 1999-February 2000), and two for the observations of carbon monoxide (scheduled as weather permits, but most likely before December 1999).

Accomplishments: Year 2

A) *Intensive 1 mm Interferometric Spectral Line Observations of Titan at OVRO*

Our program was granted two Titan transits to measure the CO(2–1) rotational transition at low spatial resolution, and one transit to measure nitriles and organics in the 236–239 GHz spectral range.

• CO(2–1): Observations of Titan were performed over two transits with OVRO on November 11 and 12, 1999, in excellent 1 mm weather. The OVRO system behaved perfectly, and perhaps the finest millimeter-wave spectrum of Titan ever recorded was measured (see Fig. 4). These unresolved observations were used to accurately measure the vertical CO profile from 40 to 300 km to be a constant 52±6 ppmv. These results were quickly analyzed and resulted in rapid publication (Gurwell, M.A., and Muhleman, D.O. 2000. "CO on Titan: More evidence for a well-mixed vertical profile", Icarus 145, 653-656).

• 236–239 GHz Spectral Line Survey: The third transit was obtained in a high-resolution configuration on December 5, 1999, with an LO setting near 238 GHz. The goals of these observations were to measure or set upper limits on the abundances of CH_3CN, CH_3C_2H, C_3H_2, and HC_3N, and to map variations in abundance (particularly latitudinally) of those species detected. Despite several system problems, Titan was strong enough to self-calibrate on the two minute timescale. The resulting continuum maps are of good quality (see Fig. 5) with resolution slightly less than the diameter of Titan (0.66″ best beam width). Several CH_3CN transitions were detected at low SNR, and possibly a CH_3C_2H line (see Fig. 6); HC_3N(26-25) was detected as well (see Fig. 7). Mapping of the spectra after application of self-calibration gains and subtraction of the continuum visibilities resulted in moderate SNR maps: the CH_3CN transitions showed no obvious variation, but HC_3N(26-25) does appear to show a weak north-south difference (Fig. 7). Using these initial results we requested and were granted an additional transit in the same configuration, as well as two further transits in the "ultra-high" configuration, with resolution of about 0.3″ at these frequencies. However, the weather in California deteriorated significantly during January, February, and March, and no further data for this project was obtained this year.

B) *High-resolution Search for C_3H_2 with the Very Large Array:*

Observations of Titan at 42.14 GHz with the VLA were performed on three consecutive nights at the end of November, 1999, in collaboration with Dr. Bryan Butler (NRAO). The goals of this project were two-fold: to search for the organic radical cyclopropenylidene (C_3H_2), and to measure latitudinal variations in temperature of the surface and lower troposphere. C_3H_2 is created through photodissociation of methylacetylene (CH_3C_2H) in the upper atmosphere of Titan, and both species are important components of the C_3 hydrocarbon photochemical scheme.

The observations were obtained in B-Array, which provided synthesized beams roughly $0.15'' \times 0.2''$. Continuum maps reduced for the first two transits are provided in Fig. 8, and show that Titan was strongly resolved. Full analysis of this data is not complete; there have been subsequent discoveries regarding the 43 GHz (Q band) system that relate to improper weighting of visibilities that are still being worked out. However, we still expect to use the continuum maps to measure latitudinal variations in the brightness temperature of Titan, which would be related to temperature variations in the surface and lower troposphere (see Fig. 9). Additionally, the time sequence of the observations will allow us to track possible temperature features on the surface as Titan revolves in its tidally locked orbit around Titan (the sub-earth longitude on Titan changed by more than 45° over the full observing period). Inspection of the spectral line observations obtained at the VLA from the first transit data set show no evidence for the C_3H_2 line, in agreement with the OVRO results at 239 GHz. These measurements will be further analyzed for all three nights, leading to publication.

Accomplishments: Year 3

A) *Intensive 1 mm Interferometric Spectral Line Observations of Titan at the OVRO Millimeter Array*

In year two, our program was granted two Titan transits to measure the CO(2–1) rotational transition at low spatial resolution, and one transit to measure nitriles and organics in the 236–239 GHz spectral range. The CO(2–1) observations were previously reported in a published paper (Gurwell, M.A., and Muhleman, D.O. 2000. "CO on Titan: More evidence for a well-mixed vertical profile", Icarus 145, 653-656).

• 236–239 GHz Spectral Line Survey: The goals of this survey are to measure or set upper limits on the abundances of CH_3CN, CH_3C_2H, C_3H_2, and HC_3N, and to map variations in abundance (particularly latitudinally) of those species detected. Strong spatial variation in nitriles and organics were measured during the Voyager flybys in the early 1980s, but the cause of the variations remain unexplained in current photochemical models.

One OVRO transit from year two was obtained in a high-resolution configuration on December 5, 1999, with an LO setting near 238 GHz. Observations clearly showed hyperfine stratospheric emission from CH_3CN and HC_3N, and the HC_3N observations suggested some north-south abundance variations, though with a beam of $0.7''$ on a $0.88''$ Titan the evidence was tentative.

We are pleased to report that based on these initial observations a new proposal was submitted in September 2000, for followup observations with the OVRO instrument, in their highest resolution configuration. We requested and were granted (as one of the highest rated proposals reviewed that year) a total of four tracks, two of which were in the high-resolution configuration. Observations were performed December 2-4, 2000 (high-res) and December 26, 2000 (medium-res), with nearly optimal system and weather performance.

These observations, when calibrated and combined, obtained a spatial resolution of $0.4''$ when Titan was nearly $0.9''$ in diameter, and clearly resolved the emission from both CH_3CN and HC_3N, with intriguing results. Figure 10 presents the integrated peak line emission from CH_3CN, which show a strong hemispheric difference in emission strength, and by extension in abundance. The pressure broadening of the lineshape suggests that the bulk of the emission comes from the 150-350 km region of the Titan stratosphere. The variations in emission (and therefore abundance) are expected to be due to photochemical and global atmospheric circulation effects. One interesting aspect is that there appears to be an east-west gradient in abundance as well, which could be explained as a photochemical enhancement of CH_3CN during periods of sunlight (e.g. on the dayside of Titan) that is entrained in a global prograde zonal wind circulation, creating and excess of the molecule on the afternoon (right side of figure) relative to the morning (left side).

Figure 11 presents the line emission for the HC_3N (26-25) rotational transition. The emission line is very narrow, unresolved at a spectral resolution of 1 MHz, implying that the emission arises from altitudes above 325 km, where pressure broadening of the lineshape is minimal. This map also shows strong hemispherical variation, with a strong peak of emission near the northern pole, a near absence of the molecule in the mid-southern latitudes, and a secondary peak near the southern pole. Note that this gradient is in the opposite sense for the CH_3CN data. As with the CH_3CN observations, the hemispheric differences are presumed to be from the complex interplay of photochemical and global circulation effects. Unlike the CH_3CN observations there do not appear to be major east-west variations. This may be because HC_3N has a longer photochemical lifetime and the expected strong zonal winds are too fast for temporal (day-night) effects to register, or it could mean that at the higher altitudes probed by the HC_3N observations there is little (or very slow) zonal circulation.

We will continue to analyze these observations in the context of 1 and 2-dimensional photochemical models, summarize our findings in a peer-reviewed paper, and make suggestions and predictions for the Titan portion of the Cassini/Huygens mission.

Accomplishments: Year 4 (Extension Year)

Intensive 1 mm Interferometric Spectral Line Observations of Titan at the OVRO Millimeter Array

A proposal to spatially resolve HCN(3-2) at 265 GHz with the OVRO array was submitted and accepted during this year. However, very poor weather during the observing season in California prohibited its execution.

However, all was not lost. The PI, as a member of the science team of the Smithsonian Submillimeter Array (SMA), obtained two high quality tracks of HCN and other nitriles at 354 GHz using the SMA in January and March 2003. The spectra are shown in Figures 12 and 13. These remarkable spectra contain the HCN(4-3) v=0 emission core in the upper sideband, along with the HCN(4-3) v=2 emission, and HC_3N(39-38) emission, as well as the $HC^{15}N$(4-3) emission line in the lower sideband. The three HCN-related lines are extremely useful, since we will (a) use the main line and its isotope to measure the $^{14}N/^{15}N$ ratio, (b) use the isotope line to measure the HCN globally averaged profile, and (c) use the main line and the vibrationally excited line to precisely measure the globally averaged upper atmospheric temperature. Work on these very recent data continues.

Finally, with the consent of Discipline Scientist for Planetary Astronomy Dr. John J. Hillman, we requested and were granted an allowance to shift remaining funds for this grant toward planning and operational expenses related to planetary atmospheric astronomy of Mars and Venus using the Submillimeter Wave Astronomy Satellite (SWAS). The initial request and Dr. Hillman's consent are presented in Appendix A.

References

Gurwell, M.A., and Muhleman, D.O. 1995. CO on Titan: Evidence for a well-mixed vertical profile, *Icarus 117*, 375-382.

Gurwell, M.A., and Muhleman, D.O. 2000. CO on Titan: More evidence for a well-mixed vertical profile, *Icarus 145*, 653-656.

Toublanc, D., J.P. Parisot, J. Brillet, D. Gautier, F. Raulin, and C.P. McKay 1995. Photochemical modeling of Titan's atmosphere, *Icarus 113*, 2-26.

Yung, Y.L., M. Allen, and J.P. Pinto 1984. Photochemistry of the atmosphere of Titan: Comparison between model and observations, *Ap. J. Suppl. 55*, 465-506.

Yung, Y.L. 1987. An update of nitrile photochemistry on Titan, *Icarus 72*, 468-472.

Appendix A: Request and Consent for Transfer of Remaining Funds

Initial Request

17 January 2003

Dr. John J. Hillman
Solar System Exploration Division
Code SE
Office of Space Science
NASA Headquarters
Washington, DC 20546-0001

Dear Dr. Hillman,

Thank you for your quick response to my earlier message. As we discussed Wednesday, I am providing below a more detailed explanation of how I would like to utilize the remaining funds in my Planetary Astronomy grant (NAG5-7946) to support planetary atmospheric studies using the Submillimeter Wave Astronomy Satellite (SWAS).

Please let me know if the following is sufficient detail. At my end, all my administrating officer will require is a simple reply that you have reviewed this request and have agreed to the altered use of the funds. I understand that you as NASA's representative may need more; I am ready to fax you a complete cost accounting of how the funds are to be spent if you find the information below lacking in detail.

Thank you again for your consideration of this request. It was a pleasure speaking with you, and am sure we will talk again soon, if not about this request, then regarding the SWAS unsolicited proposal under preparation.

Sincerely,

Mark Gurwell

REQUEST: To change the allocation of grant funds for Planetary Astronomy Grant NAG5-7946. The request is to use $22,738.00 of the remaining grant funds for salary support of three key individuals in the Submillimeter Wave Astronomy Satellite project for the analysis of recent planetary data (Venus) and preparation and planning for upcoming planetary observations of Mars and particularly Venus in 2004.

BACKGROUND: NAG5-7946 (P.I. Mark A. Gurwell, CfA) was submitted in response to the 1998 NASA ROSS call for proposals to Planetary Astronomy, and granted the fully requested budget of roughly $30K. The focus of the proposal was to use millimeter and submillimeter wave techniques to observe planetary atmospheric molecular line signatures. The data would be used to determine atmospheric conditions such as temperature structure and molecular species abundance, with the primary target being Titan. The requested budget was primarily for travel support to/from various observatories to gather and do initial analysis of the data.

At the time of the proposal, most observatories that the PI planned to utilize to gather the data did not routinely allow remote observing capability (service observing), so several trips were projected for the length of the proposal. However, through advances in observing technology (as well as judicious combinations of trips) the grant has seen significant savings on these travel costs.

The PI has continued to develop innovative observing strategies that complement the goals of the above grant. In particular, he has been a key advocate for pushing submillimeter wave observations of planetary atmospheres such as Mars and Venus using SWAS. The SWAS observations measure the column structure of water vapor in these atmospheres, as well as the temperature structure and set upper limits to the oxygen abundance. These atmospheres provide a wonderful comparative context for the observations of Titan, as well as being interesting in their own respects.

The SWAS mission, a NASA SMEX space observatory to study the distribution of water and oxygen in the galaxy through submillimeter observations, was launched in December 1998. SWAS is the only observatory capable of direct observations of water, and has shown its flexibility in solar system science by detecting water in the atmospheres of Jupiter, Saturn, and Mars as well as from several comets. SWAS observations were also obtained during the 2001 Mars opposition and dust storm, and were unique in their sensitivity to changes in the upper atmospheric temperature at that time.

The SWAS mission is poised to contribute further to our understanding of the atmospheres of Mars and Venus through potential observations of each in the coming year. Venus is a difficult target due to its proximity to the Sun, but careful technical planning will allow observations at certain times when SWAS is in earth-shadow. The SWAS observations will allow the direct detection of water in the middle atmosphere just above the cloud tops. In addition, the 2003 opposition of Mars will be the closest approach to earth in several decades, providing an unprecedented 'close-up' of the red planet during a time when dust storms are most prevalent.

The PI wishes to support these excellent opportunities to explore and characterize the atmospheres of Venus and Mars. He requests that $22,738.00 of the NAG5-7946 grant be used for salary support of three key SWAS individuals during February and March 2003 for assistance in the data reduction and analysis of recent planetary atmospheric data and for advance planning and preparation for Mars and particularly Venus. Budget details are provided below, and a full budget breakdown is available.

WORK BREAKDOWN:

1) The PI Mark Gurwell will still be responsible for the final calibration and analysis of all the planetary spectra obtained. This includes the development of specialized software for the calibration and inversion of the spectral data for temperature and/or species abundance. He reserves a small portion of the budget for travel in support of analysis of previous Titan data. His participation continues to be at no cost to NASA and this grant.

2) Dr. Edwin Bergin and Dr. Di Li of the SWAS project will provide detailed support for the acquisition and calibration of SWAS planetary data, including the development of specialized retrieval methods for accessing the data. They will assist in assessment of data quality and explore calibration alternatives to assure the highest science return from these ambitious observations. They will also provide input during the analysis of the results, particularly regarding chemical modeling and analogies to the ISM for Titan, Mars, and Venus. For the extent of the grant period they will each provide 128 hours charged to this grant.

3) Dr. Steven Kleiner of the SWAS project will provide technical support for planning the Mars and Venus observations. The Venus observations in particular require very careful consideration due to their challenging requirements of maintaining the SWAS spacecraft in a safe orientation in the Earth's shadow while still observing Venus. For the extent of the grant period he will provide 56 hours charged to this grant.

Response by Dr. Hillman

18 Jan 2003

Dear Mark,

Thank you for your very complete and quick response to my request. After reviewing the proposed plan for unspent funds from your Planetary Astronomy grant (NAG5-7946) to support planetary atmospheric studies using the Submillimeter Wave Astronomy Satellite (SWAS) I conclude it is certainly in NASA's best interest to support you in this endeavor. I approve of the plan that you outline below. I need no other paperwork to support this action. If you have any questions regarding the unsolicited proposal under preparation just ask. Please consider keeping me informed about the conclusions regarding advance planning and preparation for the future Mars and Venus observations.

Regards,

Dr. John J. Hillman, Discipline Scientist
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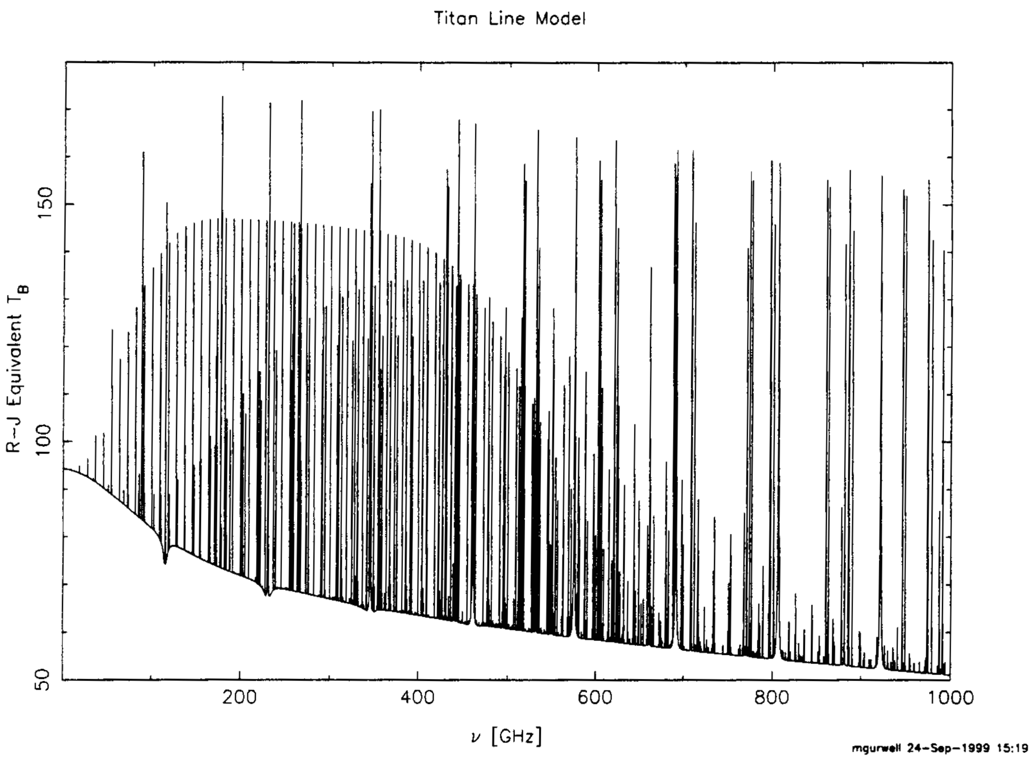


Figure 1. Results of the Titan Line Model radiative transfer code developed for this grant. The model includes rotational transitions for 15 species and isotopic variants (over 12000 lines), as well as induced dipole absorption from N_2 and CH_4.

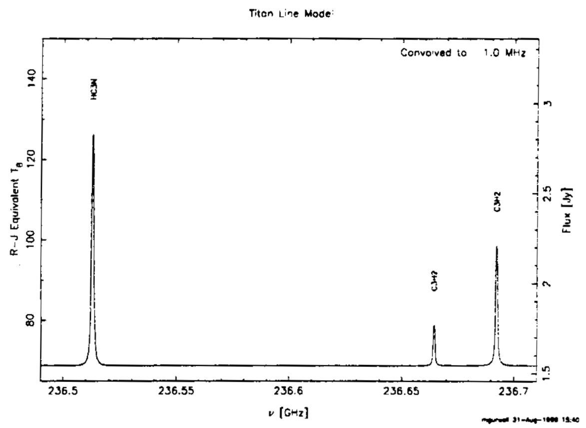


Figure 2. Model for OVRO LSB observations of Titan to be performed in December 1999 or January 2000, with the goal to detect hemispheric variations in HC_3N, by resolving Titan's 0.8″ disk with a ~0.35″ beam.

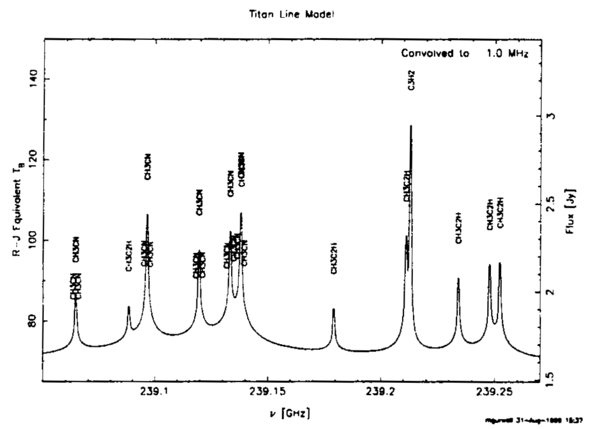


Figure 3. Model for OVRO USB observations of Titan to be performed in December 1999 or January 2000, with the goal to detect hemispheric variations in CH_3CN and to detect CH_3C_2H and C_3H_2.

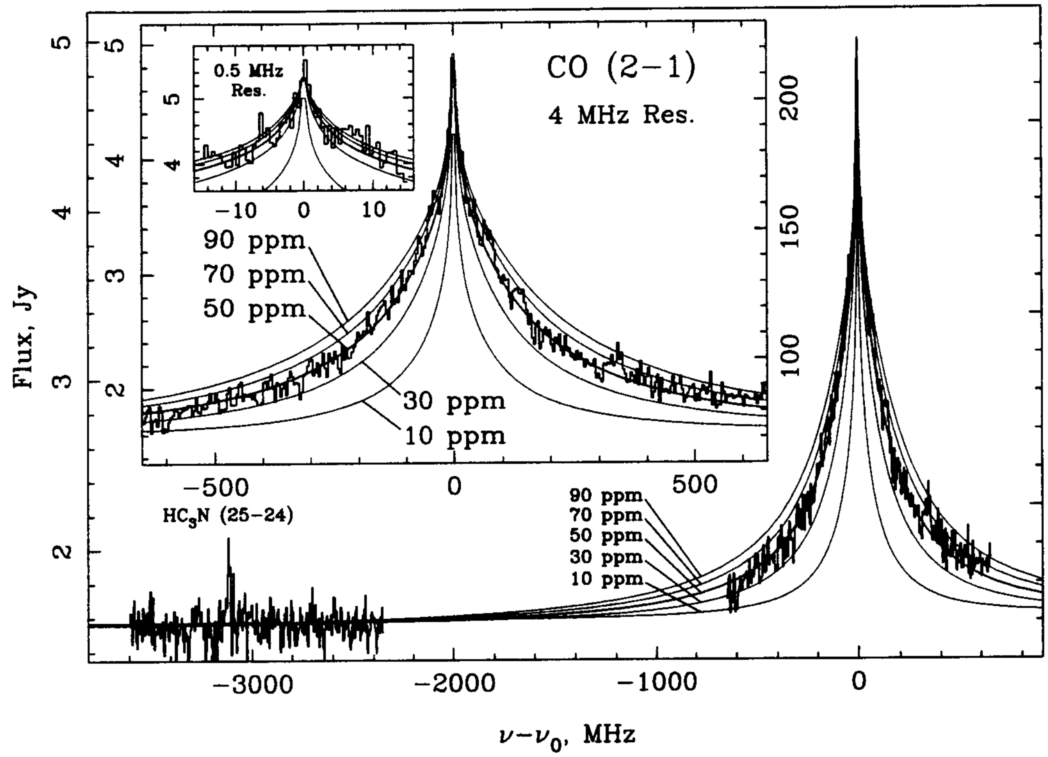


Figure 4. CO(2–1) spectrum measured November 11-12, 1999 using OVRO observations. This high SNR spectrum shows that the abundance of CO is 52±6 ppm in the stratosphere, contradicting the recent results of Hidayat et al. (1998), but in excellent agreement with results obtained from OVRO observations of CO(1-0) (Gurwell & Muhleman, 1995).

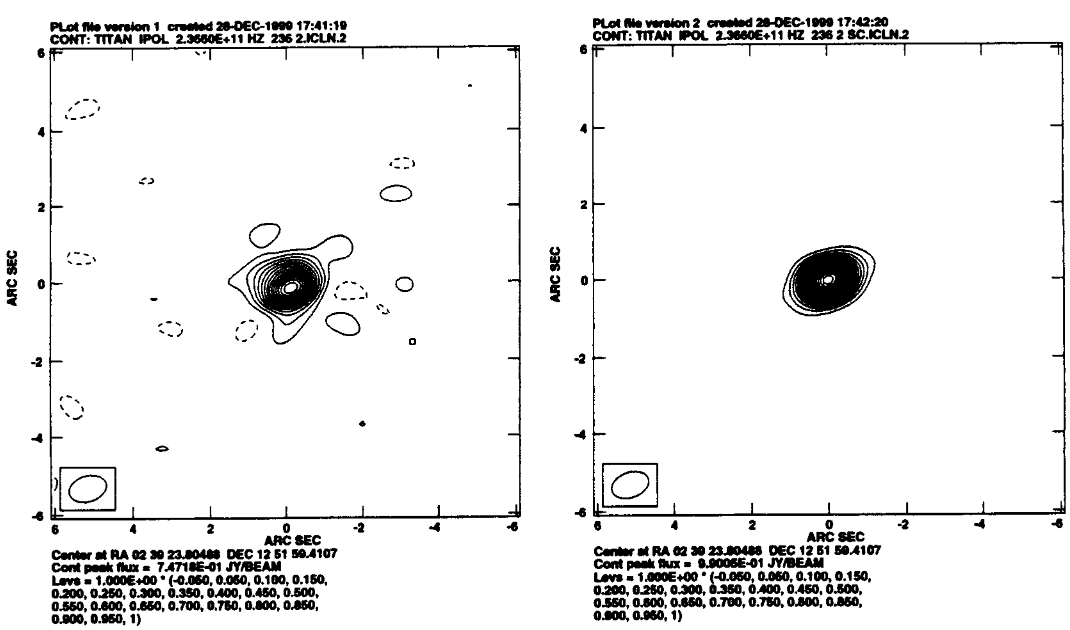


Figure 5. Continuum maps of Titan derived from one H track (December 5, 1999) at 236.5 GHz, when Titan was 0.85″ in diameter. (left) Before and (right) after self-calibration. The synthesized beam was 990×650 mas (PA -62.5°), marginally resolving Titan in the north-south direction. The dynamic range in the self-calibrated map is greater than 125 (∼8 mJy RMS). Contours are every 50 mJy.

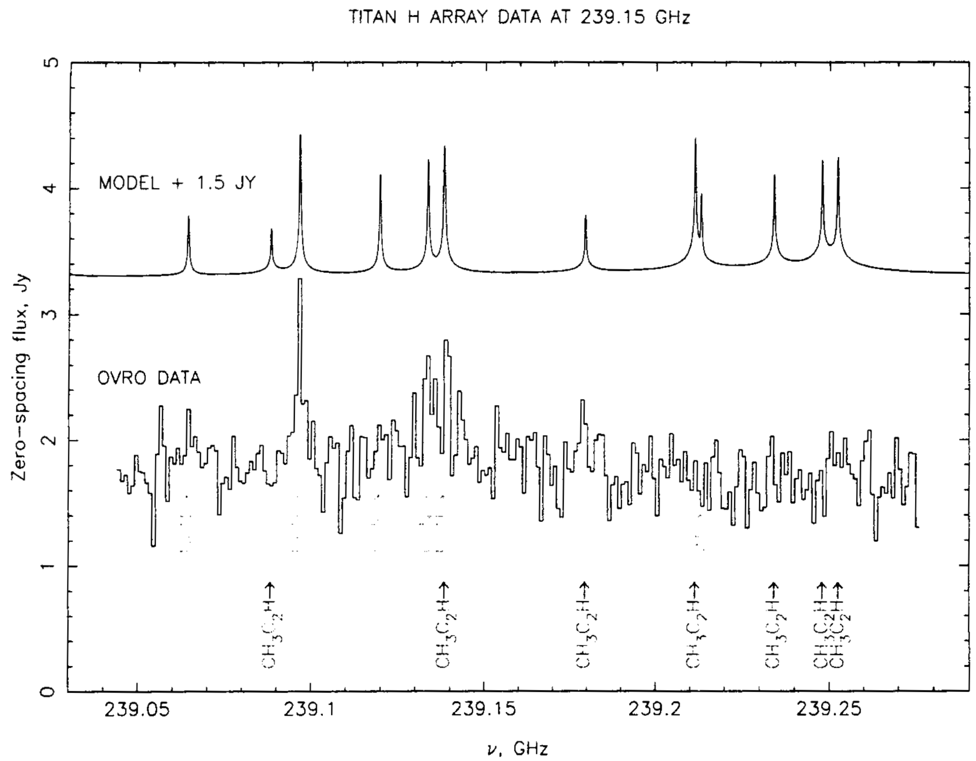


Figure 6. Extrapolated zero-spacing flux spectrum obtained through visibility fitting of Titan observations near 239.15 GHz. Also shown is a radiative transfer model of the Titan atmosphere, and individual molecular transitions are marked. We report detection of 4 out of 5 CH_3CN transitions in the band, and a possible detection of one CH_3C_2H transition. Mapping of this data showed no obvious variation in line strengths across the disk of Titan, though resolution of the experiment just barely smaller than Titan.

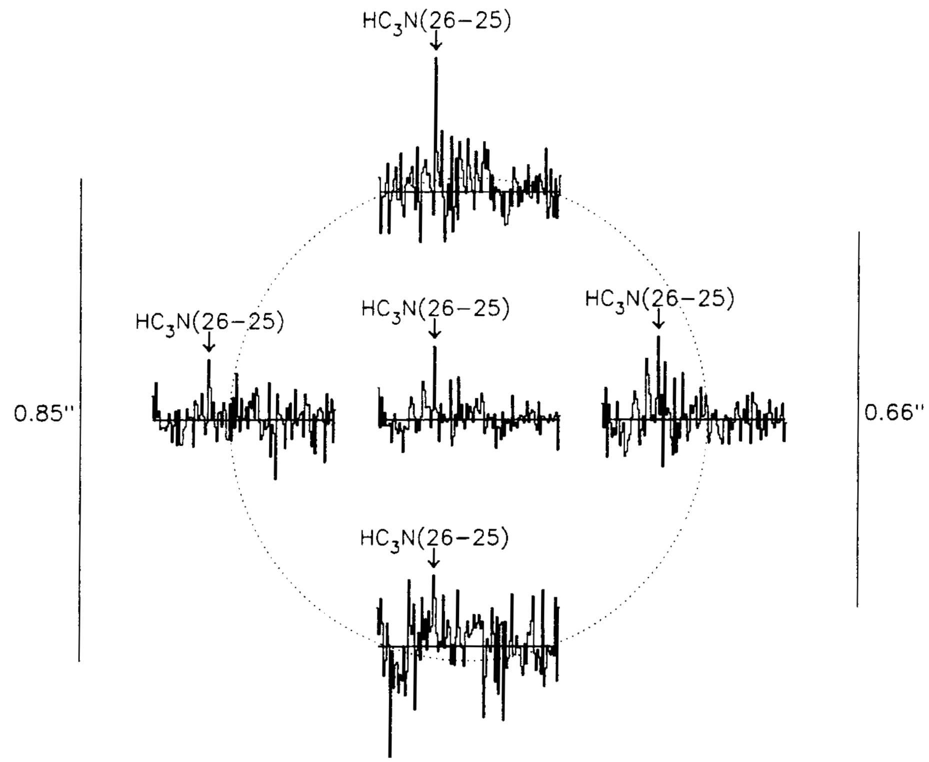


Figure 7. Mapped spectra of the HC_3N(26-25) rotational transition, after self-calibration and subtraction of the continuum channel visibility data (see Fig. 2). Spectra are plotted every 0.4″ from the disk center, and suggests an increase in the line strength from south to north, though additional integration time will provide a marked improvement in the SNR and strengthen this result. Bandwidth shown is 112 MHz.

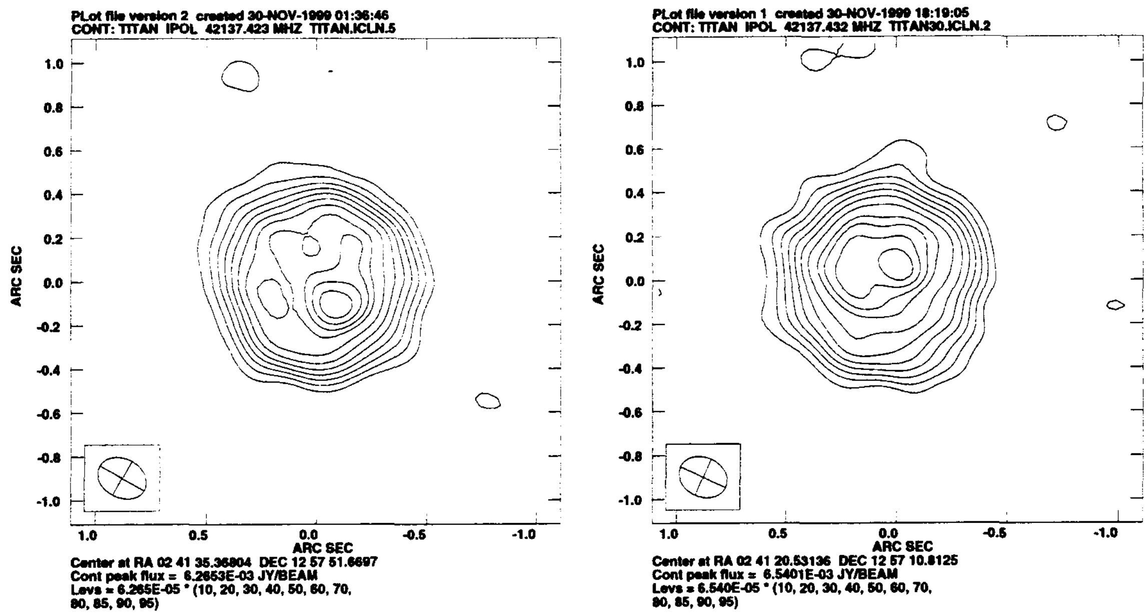


Figure 8. VLA 7mm continuum maps of Titan obtained 28 November 1999 (*left*) and 29 November 1999 (*right*) at 42.14 GHz. Data of similar quality was also obtained 30 November 1999. The synthesized beam for each night was roughly $0.15'' \times 0.20''$, providing well-resolved measurements of the thermal flux from Titan's disk ($d = 0.85''$). The resolution is comparable to the best ground-based (non-adaptive optic) images of Titan's surface in the near-IR and sufficient to identify surface temperature features if they exist, with the tidally-locked rotation of Titan providing a reference for tracking these features over the three day period. The continuum data from these three nights will provide a strong constraint on the latitudinal temperature gradient of the surface and lower atmosphere. Additionally, The data set also includes spectral line measurements of C_3H_2, which was not detected in our preliminary analysis. The VLA observations and analysis were performed in collaboration with Dr. Bryan Butler (NRAO).

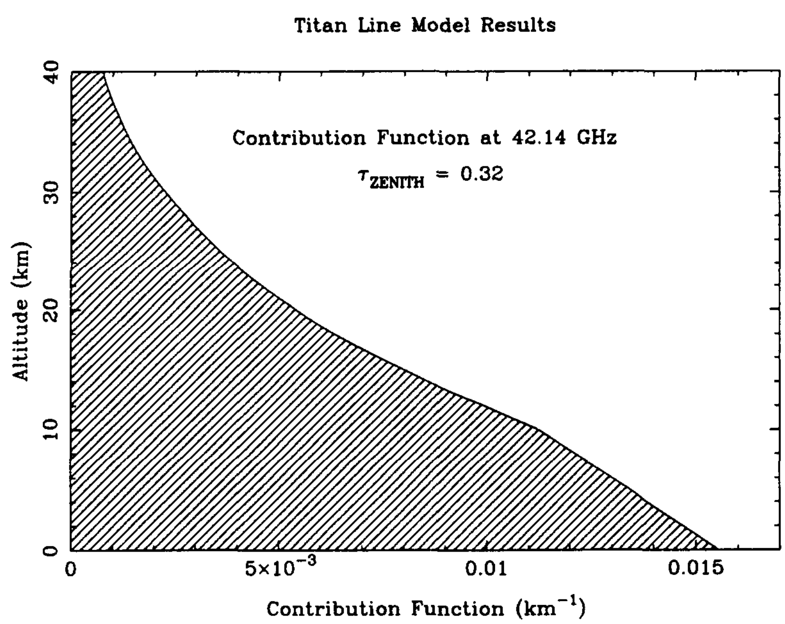


Figure 9. The atmospheric contribution to the emitted radiation at 42.14 GHz, modeled using support programs for the Titan Line Model (developed under this grant in Year 1, and discussed in the Year 1 Progress Report). We calculate that at 42.14 GHz, approximately 27% of the emitted radiation in the zenith direction is from the atmosphere, with the remaining 73% from the surface. As shown, we are increasingly insensitive to the atmosphere above 10 km. This model shows that with the VLA continuum observations we will be able to measure temperature variations in the surface and lower atmosphere, which (to our knowledge) no other observations at any wavelength have been able to provide.

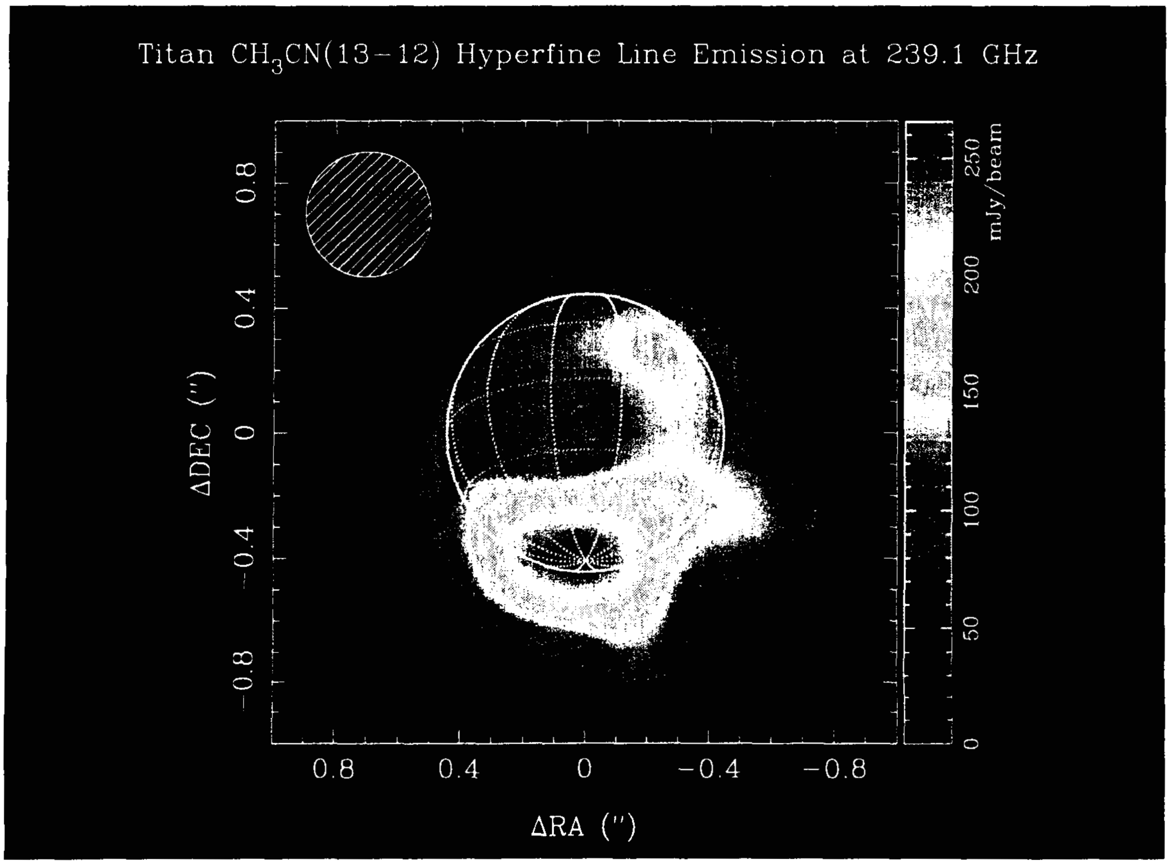


Figure 10. Integrated peak CH_3CN (13-12) rotational line emission from the stratosphere of Titan. The data were obtained in December 2000 with the OVRO Millimeter Array, operating in its highest-resolution configuration. *Titan, at 0.9″ for these observations, was for the first time at millimeter wavelengths clearly resolved with a synthesized beam of 0.4″.* The emission near each of five hyperfine transitions in a band near 239.1 GHz has been integrated to show the spatial variation of the emission. There are clear hemispherical differences that a presumably due to differences in photochemistry and global circulation between the north and south. In addition, there is evidence of an east-west variation as well. Due to the nature of the observations, this suggests that photochemical and circulation effects increase the abundance of CH_3CN toward the late afternoon on Titan (to the west or right in the figure) assuming a zonal prograde stratospheric circulation.

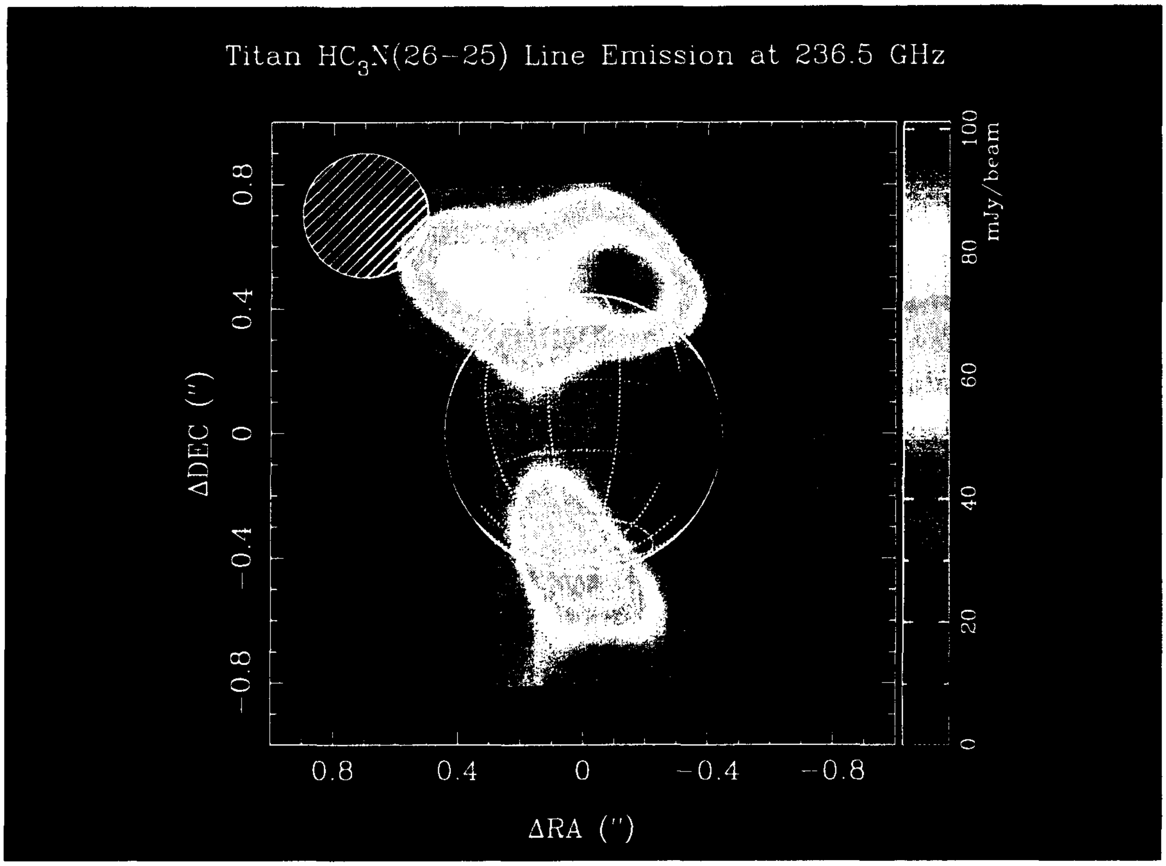
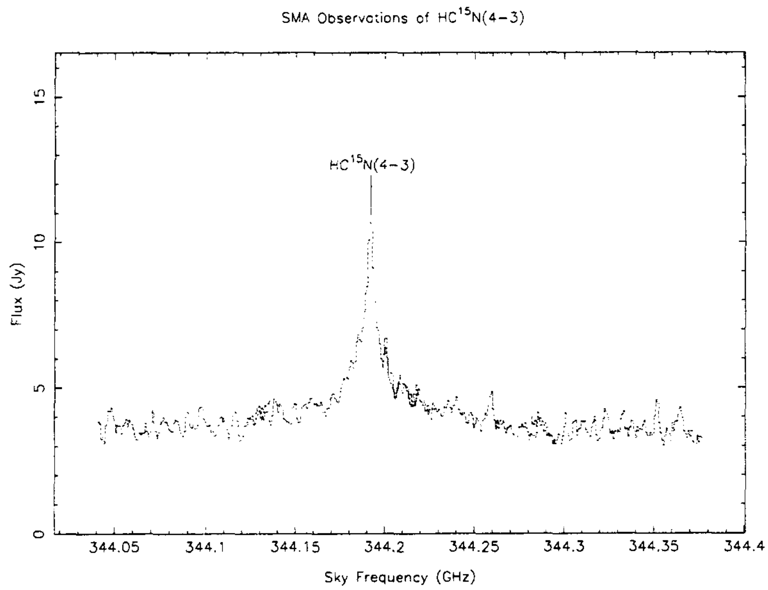
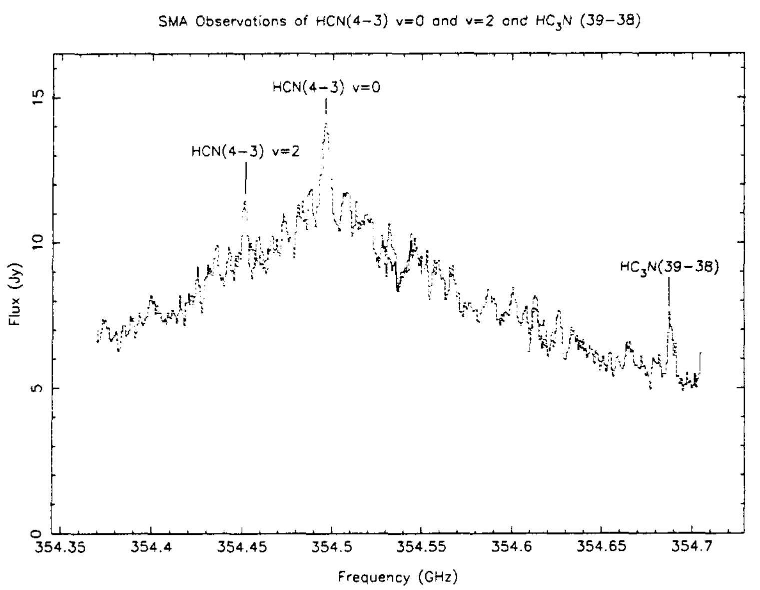


Figure 11. Integrated HC_3N (26-25) rotational line emission from the stratosphere of Titan. The data were obtained in December 2000 with the OVRO Millimeter Array, operating in its highest-resolution configuration, simultaneously with the CH_3CN observations from Figure 10. *Titan, at 0.9″ for these observations, was for the first time at millimeter wavelengths clearly resolved with a synthesized beam of 0.4″*. The emission is narrow, unresolved at the spectral resolution of 1 MHz, suggesting that the HC_3N is at altitudes above 325 km, where pressure broadening of the lineshape is small. There are clear hemispherical differences that a presumably due to differences in photochemistry and global circulation between the north and south. Note that the asymmetry is opposite that of the CH_3CN, with the peak emission coming in the northern hemisphere instead of the southern hemisphere.





Figures 12 and 13. These remarkable spectra were obtained with the Smithsonian Submillimeter Array (SMA), under development near the summit of Mauna Kea, Hawaii. The spectra contain the HCN(4-3) v=0 emission core in the upper sideband, along with the HCN(4-3) v=2 emission, and HC_3N(39-38) emission, as well as the HC^{15}N(4-3) emission line in the lower sideband. The three HCN-related lines are extremely useful, since we will (a) use the main line and its isotope to measure the $^{14}N/^{15}N$ ratio, (b) use the isotope line to measure the HCN globally averaged profile, and (c) use the main line and the vibrationally excited line to precisely measure the globally averaged upper atmospheric temperature.