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# DETECTION OF METHYL ALCOHOL IN SAGITTARIUS

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## ABSTRACT

This Letter reports observations of radio line emission at 834 MHz (36 cm), due to a *K*-type doubling transition in methyl alcohol, in the directions of Sgr A and Sgr B2. Line widths and Doppler velocities compare favorably with other molecular spectra observed toward the galactic-center region.

## I. INTRODUCTION

Methyl alcohol, $CH_3OH$, also called methanol or wood alcohol, is the simplest alcohol molecule. It brings a new level of complexity to molecular astronomy, for it is a molecule that exhibits a torsional motion called hindered internal rotation, a type of motion that has so far defied exact analysis by spectroscopists. This complexity also multiplies the number of low energy levels available to the molecule, makes some of them metastable, and provides new possibilities for infrared pumping.

We detected methyl alcohol by its *K*-type doubling line at 834 MHz (the counterpart of the 4830-MHz line of formaldehyde), using the 140-foot radio telescope at NRAO.[1] At this low frequency, the half-power beamwidth of the antenna is approximately 36 arc min, substantially larger than the beamwidths used in previous molecular observations of the galactic-center region. Even though the continuum temperatures toward the center are relatively large, greater than 100° K, the line appears in emission.

## II. OBSERVATIONS

Figures 1 and 2 show the spectra for Sgr B2 and Sgr A obtained 1970 September 1–7. Baseline curvature, discussed below, has been removed by subtracting a fitted fourth-order polynomial. Because the emission spectra are weak and because of limited observing time, no mapping of $CH_3OH$ was possible. Table 1 gives the positions used, the antenna temperature $T_L$ of the emission maxima, line widths, and Doppler velocities with respect to the local standard of rest. Upper limits are given for four other radio sources in Table 2.

Antenna illumination was obtained with a crossed-dipole feed and a two-channel transistor amplifier. Each channel had a system temperature of 550° ± 50° K. Aperture efficiency was 55 ± 5 percent, and the conversion factor from antenna temperature to flux for a point source was 3.5 ± 0.4 f.u. per ° K.

Spectral data were processed with the NRAO 384-channel one-bit digital autocorrelator. To double the effective integration time, 192 channels were used on each receiver, and the final spectra represent the average of two orthogonal linear polarizations. The spectral resolution was obtained by the equivalent of cosine weighting of the autocorrelation functions. The total power method was used to accumulate the data, with a long OFF followed by several short ONS. The advantages of this method are described by Ball

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[1] The National Radio Astronomy Observatory, Green Bank, West Virginia, is operated by Associated Universities, Inc., under contract to the National Science Foundation.

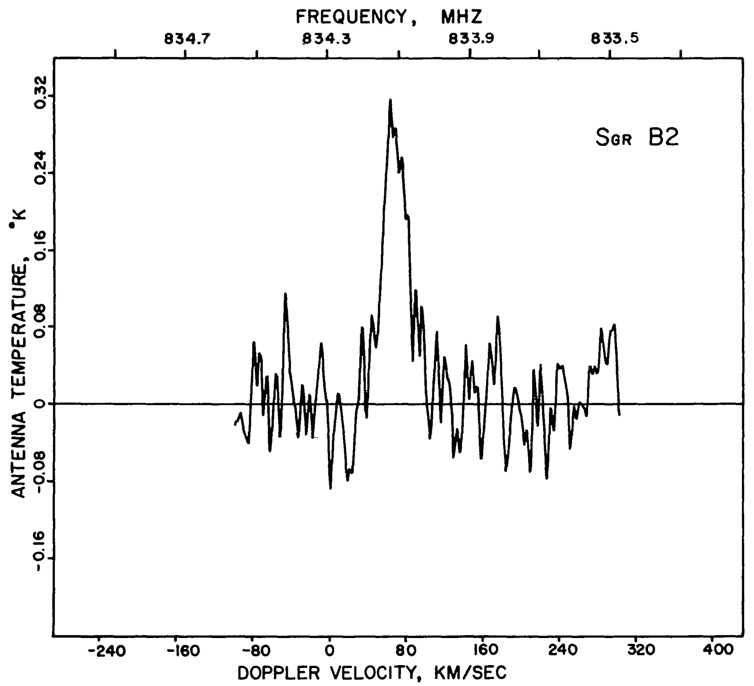

FIG. 1

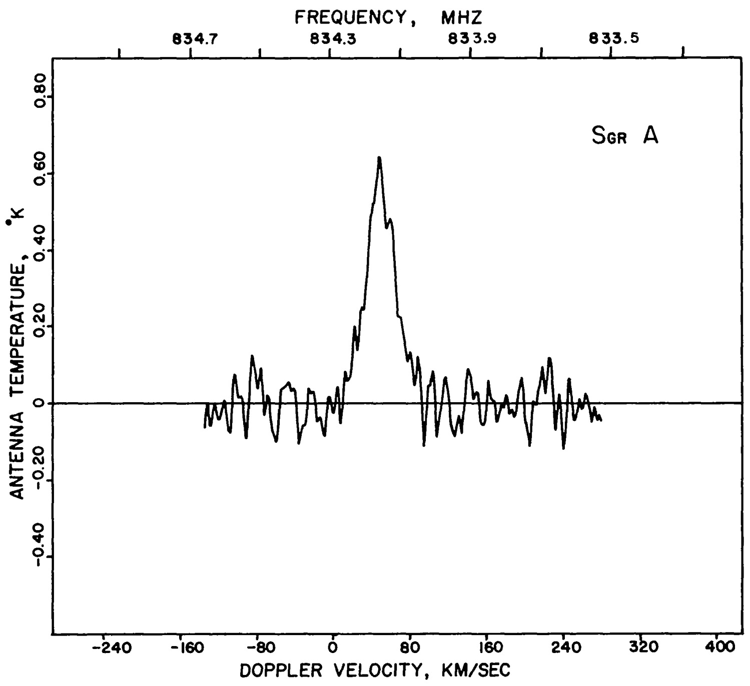

FIG. 2

FIG. 1.—Spectrum of the 36-cm line of methyl alcohol in Sgr B2. The velocity scale is based on a line rest frequency of 834.301 MHz, and both the velocity and frequency scales are referenced to the local standard of rest. The ON integration time was 1120 minutes. A fourth-order polynomial baseline has been removed. The instrumental resolution was 13 kHz or 4.7 km sec$^{-1}$.

FIG. 2.—Sgr A. The ON integration time was 1480 minutes. Otherwise all comments under Fig. 1 apply.

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(1969). Some reduction in the instrumental baseline curvature may result from this technique. Nevertheless, in the observational data the instrumental baseline curvature was not negligible, and careful system tests were performed to ensure that instrumental effects were not affecting the final spectra. The crucial baseline test uses a source with a continuum antenna temperature equal to or greater than the sources of interest. For this test the radiometric system was partially exposed to the solar continuum. Table 2 shows that no features were evident in the solar test or in an off-source test. These tests show that baseline variations do not contribute significantly to the spectra of Sgr A and Sgr B2 shown in Figures 1 and 2.

## III. IDENTIFICATION OF METHYL ALCOHOL

Identifying a solitary spectral feature like that in Figures 1 and 2 is not simple. Lacking the rigorous tests of hyperfine structure, or the detection of other lines of the same molecule (or the same line of an isotopic molecule), one must rely on a coincidence in frequency between the astronomical line and a laboratory line to establish the identification. To derive a rest frequency from the astronomical observations, one could assume "typical" molecular velocities for Sgr A and Sgr B2, but we prefer to bracket the rest frequency with Doppler shifts that correspond to the maximum velocities observed in the Sagittarius region. This range of velocities, shown by the OH absorption, is approximately +100 to −200 km sec$^{-1}$, and the corresponding range of possible rest frequencies, based on the observed "sky frequency," is 833.9–834.7 MHz.

TABLE 1

EMISSION FEATURES OF METHYL ALCOHOL

| | Pointing Position* (1950) | | Continuum Antenna Temperature | Emission Features† | | |
|---|---|---|---|---|---|---|
| Source | α | δ | (°K) | $T_L$ (°K) | Full Width to Half-Power (km sec$^{-1}$) | $V_{LSR}$‡ (km sec$^{-1}$) |
| Sgr A..... | $17^h42^m28^s$ | −28°58′30″ | 335±60 | 0.58±0.1 | 40±4 | 51±5 |
| Sgr B2.... | 17 44 11 | −28 22 30 | 140±15 | 0.30±0.1 | 35±7 | 66±9 |

* Because we measured neither the position nor the angular extent of the methyl alcohol emission, we give only the positions toward which the antenna was pointed when we obtained the spectra shown in Figures 1 and 2.

† These parameters were obtained from a least-squares Gaussian fit. The error limits are our estimates of the peak errors due to noise. No correction has been made for instrumental resolution or for hyperfine splitting.

‡ $V_{LSR}$ is the Doppler velocity with respect to the local standard of rest and a line rest frequency of 834.301 MHz. The velocity of the Sun with respect to the local standard of rest was taken to be 20 km sec$^{-1}$ toward $18^h$, +30° (1900).

Spectral lines at frequencies below 1 GHz fall into two main categories: hyperfine-structure transitions, and the various fine-structure doubling transitions (Λ-type, *l*-type, and *K*-type). Apart from a large number of beam measurements of atomic hyperfine structure, very little spectroscopy has been done in this frequency region, partly because of experimental difficulties and partly because of the scarcity of lines. The frequencies of the more intense doubling transitions come at multiples of each other, and hence are widely separated.

To search for possible alternative identifications, we scanned compilations of atomic-beam data, checked the meager literature on spectra of molecular hyperfine structure and fine structure below 1 GHz, and computed the frequencies of the strongest *K*-type doubling lines ($K = 1$) for every slightly asymmetric molecule included in the *Microwave Spectral Tables* (1968). In addition, we computed formaldehyde *K*-type doubling frequencies for *K*-values of 2, 3, and 4. We found no frequencies within the range 833.9–834.7 MHz. Also absent from this range are recombination lines of hydrogen, helium, and carbon with $\Delta n$ less than 4.

## TABLE 2

### UPPER LIMITS FOR OTHER SOURCES

| SOURCE | POINTING POSITION (1950) |  | CONTINUUM ANTENNA TEMPERATURE (°K) | VELOCITY RANGE SEARCHED ($V_{LSR}$) (km sec$^{-1}$) | "ON" INTEGRATION TIME (minutes) | $T_L$ UPPER LIMIT* °K ANTENNA TEMPERATURE | SPECTRAL RESOLUTION |  |
|---|---|---|---|---|---|---|---|---|
|  | $\alpha$ | $\delta$ |  |  |  |  | kHz | km sec$^{-1}$ |
| W3(OH)..... | $2^h23^m16^s.3$ | $+61°38'57''$ | ... | −120 to + 80 | 1024 | 0.20 | 6.5 | 2.3 |
| NGC 2024... | 5 39 12 | −01 55 42 | 16± 3 | −170 to +240 | 817 | 0.16 | 13 | 4.7 |
| Virgo A†.... | 12 28 17 | +12 39 57 | 90± 10 | −120 to +250 | 60 | 0.6 | 13 | 4.7 |
| Cas A....... | 23 21 11 | +58 32 48 | 950±100 | −250 to +150 | 180 | 0.7 | 13 | 4.7 |
| Near Sgr A.. | ... ‡ | ... | ... | −130 to +230 | 240 | 0.25 | 13 | 4.7 |
| Sun§........ | ... | ... | 1000±200 | −110 to +280 | 620 | 0.7 | 13 | 4.7 |

* Approximately equal to the peak-to-peak noise. This number corresponds to the upper limit to the received line strength averaged over the spectral resolution in either emission or absorption.

† Peaked on continuum.

‡ Eight minutes of time in R.A. offset from Sgr A.

§ To test the baseline, beam was put close enough to the edge of the Sun to get the stated continuum antenna temperature.

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By its nature, such a search cannot be completely conclusive; but because the 834.3-MHz line of methyl alcohol fits the astronomical observations so well and because we can find no other line that does, we consider the identification to be established beyond reasonable doubt.

### IV. ENERGY LEVELS AND LABORATORY MEASUREMENTS

Methyl alcohol is an asymmetric top molecule that undergoes hindered internal rotation. The energy-level diagram in Figure 3 displays the lowest levels of the ground hindered-rotation state. The $CH_3$ (methyl) group causes a threefold barrier against internal rotation, and each internal-rotation level has a threefold degeneracy. However, quantum-mechanical tunneling causes the threefold levels to split into a single level (designated $A$) and two nearly degenerate levels (designated $E_1$ and $E_2$). Electric-dipole transitions between $A$ and $E$ levels are forbidden.

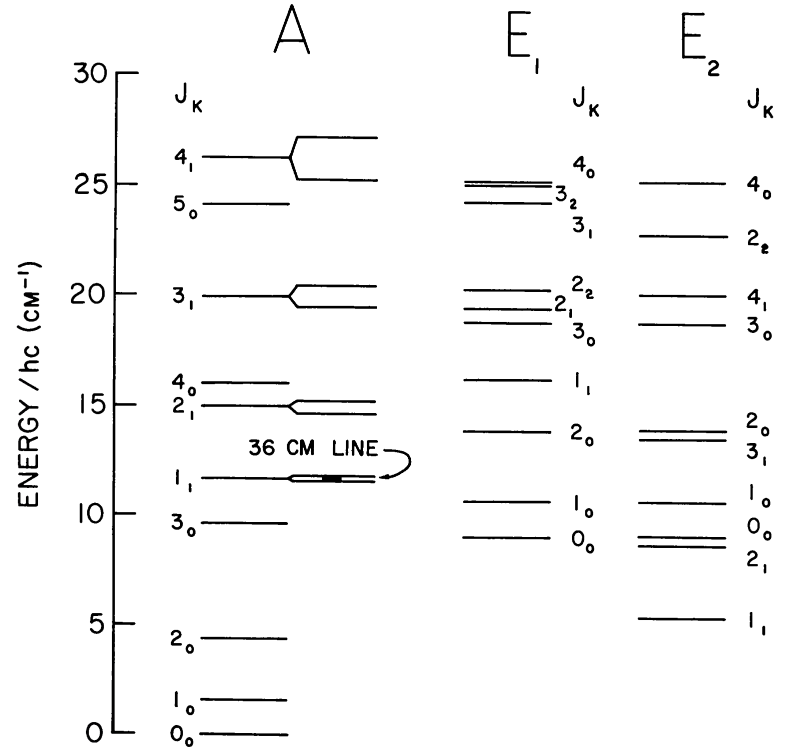

FIG. 3.—Lowest energy levels of methyl alcohol, drawn roughly to scale but with small splittings exaggerated for clarity. These levels are all members of the ground internal-rotation state ($v = 0$). Levels of the first excited internal rotation state ($v = 1$) start at 209 cm$^{-1}$. Transitions $A \leftrightarrow E$ are forbidden.

In the ground state of methyl alcohol, the $E$ levels are $\sim$10 cm$^{-1}$ higher than the $A$ level (Burkhard and Dennison 1959), and do not have transitions at low microwave frequencies. The $A$ levels exhibit a rotational spectrum quite similar to that of an asymmetric rotor (e.g., formaldehyde), including the $K$-type doubling. The 36-cm astronomical line is formed by transitions between the two levels of the lowest $K$-type doublet ($J_K = 1_1$), as indicated in Figure 3. The $K$-type doubling transitions are electric dipole in character. The Einstein $A$-coefficient for the 36-cm transition is $2.7 \times 10^{-12}$ sec$^{-1}$ if the component of the dipole moment along the symmetry axis is taken as 0.885 debye (Ivash and Dennison 1953). Unlike formaldehyde, the component of the dipole moment perpendicular to the symmetry axis is not zero, and the radiative lifetime of methyl alcohol in the $J_K = 1_1$ levels is comparatively short, approximately $10^3$ sec.

The frequency of the 36-cm line could be predicted accurately enough for an astronomical search from recent laboratory measurements of the millimeter wave spectrum of methyl alcohol (Lees and Baker 1968), but we made prior laboratory measurements of $K$-type doubling lines at higher frequencies to check this prediction, and also to convince ourselves that $K$-type doubling transitions are in fact observable in methyl alcohol.[2] After the successful detection in Sagittarius, we made a direct laboratory measurement of the 36-cm line in order to get an accurate value of the rest frequency and to investigate the possibility of unresolved hyperfine structure in the astronomical line.

The spectrometer was a resonant-cavity absorption apparatus, with methyl alcohol vapor contained in a two-liter quartz cell within the cavity. Resonant in the cylindrical $TE_{111}$ mode (with a loaded $Q$ of 20000), the cavity had a diameter of 30 cm and a length of 20 cm. The radiofrequency field configuration permitted Stark modulation to be applied to a fine wire cemented to the quartz cell, and a clamped square-wave modulation of 1500-V peak amplitude at 3 kHz was used. The cavity field was excited by a crystal-stabilized ultrahigh-frequency oscillator, and molecular resonance was detected by a superheterodyne receiver. The low-noise transistor amplifier and balanced mixer of this receiver were components of the radio telescope used for the astronomical observations, and were loaned by NRAO for this experiment.

The 36-cm absorption line is rather weak, and could not be detected at vapor pressures much below 1 millitorr. At this pressure the line width was 75 ± 10 kHz, and width measurements at higher pressure established that 50 ± 5 kHz of this was due to pressure broadening. No hyperfine structure was detectable, and from the pressure-broadening measurement we conclude that hyperfine structure does not account for more than 40 kHz (14 km $\sec^{-1}$) of width in the 36-cm astronomical line. The average result of seven determinations of the center frequency is 834.301 ± 0.005 MHz, and this value is taken as the true rest frequency in the discussion of Doppler velocities. The quoted error is our best estimate of possible systematic error, due chiefly to cavity mistuning and accidental Stark shifts. Improvements in the apparatus, now being made, should permit a considerable refinement of the rest frequency.

## V. LINE FORMATION

Because the 36-cm line of $CH_3OH$ appears in emission, the excitation temperature of this transition must certainly be higher than the brightness temperature of the background continuum, or else be negative (i.e., inverted populations). The *apparent* continuum brightness temperature for the Sgr A position, found by dividing the continuum antenna temperature by the antenna-beam efficiency, is about 400° K. However, since we do not know the angular distribution of the $CH_3OH$, we do not know the true continuum brightness behind the $CH_3OH$. It may be either higher *or lower* than 400° K.

If the angular distributions of both the $CH_3OH$ emission and the continuum emission were known, it would be possible to assign a lower limit to the excitation temperature, but even with this lower limit our data would yield a value for the column density only if we assumed a value for the excitation temperature, or vice versa. Without further observations, very little more can be said about line formation, including in particular the question of possible nonequilibrium excitation.

## VI. COMPARISON WITH OTHER MOLECULES AND CONCLUSIONS

Tables 3A and 3B show the line width and Doppler velocity of our $CH_3OH$ results compared with those for other molecules detected toward the galactic-center region.

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[2] The orientation of the dipole moment given by *Microwave Spectral Tables* (1968) would permit no $K$-type doubling transitions, and is in error.

In most cases, we selected those molecules for which mapping results are available, and those features that agree, at least approximately, in velocity. The footnotes to these tables describe the procedures used to obtain the numbers. Such a comparison with other molecules can be misleading in that it ignores differences in angular coverage, and treats absorption and emission in the same way, thus ignoring the effect of the back-

TABLE 3A

VELOCITY AND LINE-WIDTH COMPARISONS WITH OTHER MOLECULES IN SAGITTARIUS A

| Species | $CH_3OH$ | $H_2CO$* | OH $^2\Pi_{3/2}$, $J=3/2$† | CO‡ |
|---|---|---|---|---|
| Emission (E) or absorption (A).... | E | A | A | E |
| $V_{LSR}$ (km sec$^{-1}$).................. | 51±5 | 23–51 | 36.6 | 17–60 |
| $\Delta V$ (km sec$^{-1}$).................... | 40±4 | (38) | 55 | 52 |

TABLE 3B

VELOCITY AND LINE-WIDTH COMPARISONS WITH OTHER MOLECULES IN SAGITTARIUS B2

| Species | $CH_3OH$ | $H_2CO$* | OH $^2\Pi_{3/2}$, $J=3/2$† | $NH_3$§ | CO‡ |
|---|---|---|---|---|---|
| Emission (E) or absorption (A)..... | E | A | A | E | E |
| $V_{LSR}$ (km sec$^{-1}$)................... | 66±9 | 61.6 | 60 | 32–64 | 27–100 |
| $\Delta V$ (km sec$^{-1}$)..................... | 35±7 | 26.3 | ~50 | ... | 58 |

* From Zuckerman *et al.* (1970). The $V_{LSR}$ range is for the largest positive-velocity features, which are typically the most opaque. The number in parentheses is the average line width of the same features. For Sgr B2 only one position is available.

† From Palmer and Zuckerman (1967), as cited in Zuckerman *et al.* (1970). The width given for Sgr B2 is an estimate for the higher-velocity component in a complex feature.

‡ Penzias *et al.* (1970) tabulated the radial velocity of the half-intensity points of each CO emission profile, and we used the center of these points as a rough measure of the CO radial velocity. The range in this center velocity is the quantity tabulated as $V_{LSR}$, and $\Delta V$ is the mean width.

§ From Cheung *et al.* (1969).

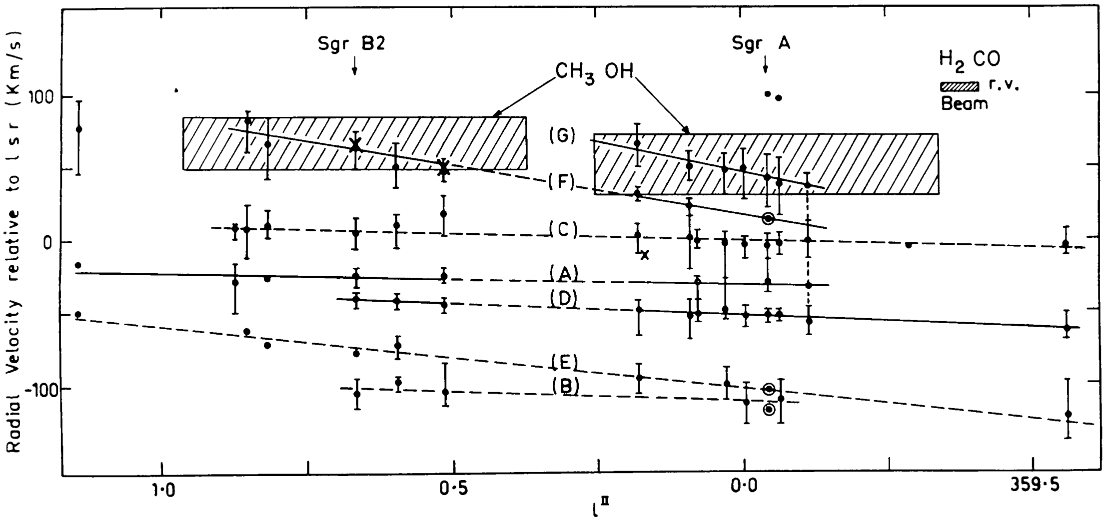

FIG. 4.—Distribution with galactic longitude of the velocities of the absorption peaks in $H_2CO$ from Gardner and Whiteoak (1970), with our $CH_3OH$ results superimposed. Vertical lines show the half-widths of $H_2CO$ absorption components. The widths of the shaded rectangles represent our 36′ beam-width, and the heights represent the observed half-widths in $CH_3OH$. For other details in the figure, see Gardner and Whiteoak (1970).

ground continuum and the possibility of different spatial distributions of molecular species. In spite of these effects and precautions, we note that the velocity ranges (center velocities *and* widths) of the other molecules in Tables 3 and 4 overlap the velocities of $CH_3OH$. Because of the chemical similarity of methyl alcohol and formaldehyde, we have plotted our $CH_3OH$ results on the $H_2CO$ mapping results of Gardner and Whiteoak (1970) as shown in Figure 4. Although further observations are needed, this comparison suggests that the $CH_3OH$ emission is associated with the same clouds that cause the strongest $H_2CO$ absorption.

We thank Joseph Onello for help in detecting the astronomical line and Douglas Pitman for help in measuring the laboratory line. The staff of NRAO was especially helpful, particularly W. E. Howard and Michael Ballister, who did considerable extra work for our benefit. We thank F. F. Gardner, J. B. Whiteoak, and the editor of *Astrophysical Letters* for permission to reproduce Figure 4. This work was supported in part by the National Science Foundation through grant GP-19717.

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