

II. GALACTIC 21-CENTIMETER OBSERVATIONS IN THE DIRECTION OF 35 EXTRAGALACTIC SOURCES

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ABSTRACT

A detailed comparison of emission and absorption spectra obtained in the direction of extragalactic sources permits an unambiguous separation of the contribution from a diffuse, high-temperature, optically thin component and that from denser and colder local concentrations of hydrogen. The concentrations have a mean column density $N_{\text{H}_0} \approx 3 \times 10^{20}$ atoms cm^{-2} and a spin temperature $T_s \approx 60^\circ\text{--}80^\circ\text{K}$. They are typically separated along a line of sight by one full scale-thickness of the galactic disk. The diffuse intercloud medium has a column density $N_{\text{H}_1} \approx 1.4 \times 10^{20} \text{ cosec } |b|$ atoms cm^{-2} , a spin temperature in excess of 750°K , and contains half of the total mass of hydrogen in the solar neighborhood.

I. INTRODUCTION

It has long been noted that 21-cm absorption spectra differ considerably from emission spectra obtained in the same part of the sky. The absorption spectra show features characteristically narrower than the corresponding emission features. This difference was originally attributed to the averaging effect of the antenna beam, which naturally included many more hydrogen clouds than the ones directly in line with the continuum source. In this picture it was implicitly assumed that there was no great variation of the temperature from region to region and that the density distribution alone was the determining factor in the form of the various spectra. An alternative interpretation was advanced by Clark (1965), who suggested that temperature differences were in fact the prime cause of the dissimilarities. Based on the then most extensive 21-cm absorption study, he proposed a "raisin pudding" model, in which dense cold concentrations were embedded in a hot, tenuous medium with temperatures for the two components being respectively less than and very much greater than the 125°K estimated from emission studies. In Clark's model the cold absorbing concentrations or clouds were analogous to the clouds hypothesized in the earlier model as far as their role in absorption spectra was concerned. The important difference was the postulate of an optically thin high-temperature medium whose presence could be detected only in the associated emission spectra.

A limited knowledge of the gas temperature can be gleaned from emission studies of neutral hydrogen based on the width of the spectral features and the brightness temperature of the emitting regions. A maximum limit on the kinetic temperature, for example, can be obtained on the assumption that the line broadening is entirely thermal and that turbulent motions have contributed negligibly to the observed width. Similarly, a minimum limit for the spin temperature is given by the observed brightness temperature. Since the spin temperature is essentially determined by collisions and is therefore equal to the kinetic temperature, a special case can be imagined in which these two limits coincide. Such a coincidence would lead uniquely to a determination of the spin (or kinetic) temperature from a simple measurement of the emission profile. Usually, however, there is a large region of overlap between the two limits. Ignorance of the optical depths and the prevalence of turbulent and other motions then combine toward providing only a crude estimate for the mean spin temperature from emission studies and no information at all about its variation from region to region.

A measurement of both the optical depth and the brightness temperature of a sample of interstellar neutral hydrogen would in principle enable a determination to be made of the spin temperature, provided the sample were isothermal. The true column density of the sample could be calculated from such measurements free of the customary assumption of optical thinness. By comparing the observed widths of the lines with the expected thermal broadening the internal turbulence can also be assessed. Absorption and emission measurements in the direction of a number of suitably chosen sources should therefore provide the data necessary for calculating representative values of a number of important parameters.

It is natural to expect stronger absorption in the direction of sources lying close to the galactic plane where the neutral hydrogen is concentrated. This expectation is amply borne out by the observations reported in the two papers following this one, where attention was confined to sources at very low galactic latitudes. Such observations, however, throw more light on the source distances and the mean density of absorbing neutral hydrogen in the plane than on the temperature structure of the gas. To obtain information on the temperature it is essential that both the absorption and emission measurements refer to the same sample of gas. To satisfy this requirement the continuum source should be located beyond all of the hydrogen seen in emission in that direction. Further, since the emission profile must necessarily be obtained away from the precise direction of the discrete source, it is desirable that the distribution be uniform over an area of sky large compared with the antenna beam. The nearest approximation is achieved by making observations on extragalactic sources situated at intermediate or high galactic latitudes. At these latitudes the highly flattened nature of the galactic hydrogen distribution ensures a minimal linear displacement for a given angular displacement of the antenna beam.

All previous investigations of 21-cm absorption were directed toward detecting and measuring absorption in the spectra of strong discrete sources. In those studies no thought was given to obtaining emission spectra originating only in the gas whose optical depth was being determined. It appeared, therefore, that we could best achieve an unambiguous identification of the optically thin component by a close comparison of emission and absorption spectra obtained with the same frequency resolution and under conditions where both spectra could be relied upon to refer to the same sample of gas. The observations reported in this paper were undertaken primarily toward this end. Under these circumstances, if all the hydrogen were at the same temperature, one would expect the absorption profile in a given direction to mimic closely the form of the corresponding emission profile; the brightness temperature is a function of the optical depth and is in fact directly proportional to it for small depths. As we shall show presently, the fact that certain differences persist between the two types of spectra demonstrates the existence of widely different spin temperatures in the distribution of neutral hydrogen.

The main inferences from the present work supporting a two-component model have already been published from a preliminary analysis of the observations (Radhakrishnan and Murray 1969). Similar conclusions were also reached by Mebold (1969), who reanalyzed published measurements of 21-cm absorption spectra and found large variations in the spin temperature of the neutral hydrogen. On the theoretical side there have been a number of papers over many years hypothesizing the existence of a high-temperature component of the interstellar hydrogen heated by low-energy cosmic rays. Field, Goldsmith, and Habing (1969), for example, predicted a hot phase of the gas at a temperature of approximately 10^4 ° K. In this paper we present the data on which our initial conclusions were based and discuss some further aspects of interest.

II. SOURCES OF ERROR

The 35 sources whose 21-cm spectra were investigated range in galactic latitude from 6° to 74° . Their distribution in galactic coordinates is shown in Figure 1.

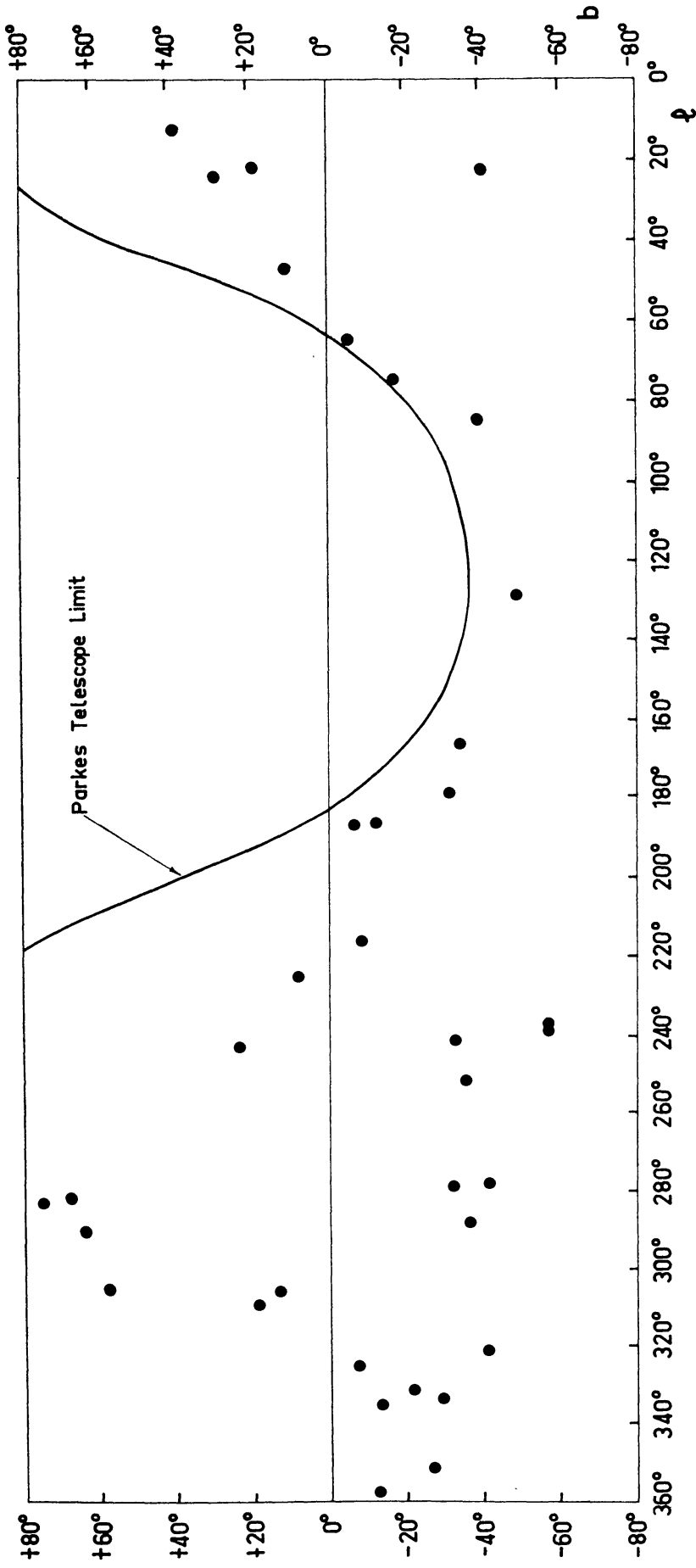


FIG. 1.—Distribution in galactic coordinates of the 35 extragalactic sources whose 21-cm spectra were investigated

Emission and absorption measurements on all of the sources were made by use of the Parkes 64-m reflector. For these measurements, a frequency-switched radiometer was used together with a 64-channel spectrometer (Batchelor, Brooks, and Sinclair 1969), which provided a choice of 1, 10, 33, or 100 kHz for the filter bandwidths.

Fifteen of these sources were also observed with the interferometer described in Paper I (Radhakrishnan *et al.* 1971a). The primary beamwidth of the interferometer was $18.5'$, and at the operating baseline of 120 m north-south the zenith fringe separation was of the order of $6'$. The interferometric method for absorption measurements has been dealt with in detail in Paper I.

The standard procedure for single-dish observations was to obtain profiles in the direction of the source and in directions displaced by one beamwidth ($15'$) to the north, south, east, and west of the source. The average of these four profiles (labeled NSEW in the figures) formed the reference emission profile, which was assumed to approximate closely the emission profile that would have been obtained in the direction of the source in its absence. Marked variations in the emission with an angular scale size $\leq 15'$ are commonplace at very low galactic latitudes, and numerous examples may be seen in the observations reported in Papers III and IV of this series (Radhakrishnan *et al.* 1971b; Goss *et al.* 1971). Even at latitudes well off the plane some variations must still be detectable. To obtain an estimate of these variations we have made measurements on the two standard regions S8 and S9 recommended by the IAU (Van Woerden 1967) as regions of relatively uniform emission. These regions are situated at latitudes of 15° and 4° , respectively, and it was suggested that they could be used for the intercomparison of 21-cm brightness-temperature scales adopted by observers who used widely differing antenna beamwidths.

In Figures 2 and 3 we present measurements on these regions. The profiles marked S8 and S9 refer to the centers of these regions. The profiles marked S8-NSEW and S9-NSEW represent the differences between the two former profiles and approximations to them obtained by averaging regions one beamwidth away. It is seen that errors of a few degrees Kelvin are still present. These errors would have invalidated absorption measurements made on sources situated at these positions and having antenna temperatures of the same order or less. The advantage of observations at intermediate and higher latitudes is that single-dish measurements of absorption can be made on weaker sources than would be possible in the galactic plane. But at any latitude, depending on the size of the telescope, there is some limiting source intensity below which emission variations introduce overwhelming errors.

In the case of regions free from continuum sources, like S8 or S9, pseudo-absorption measurements as described above can be made to determine the errors that would have been introduced. For obvious reasons, regions containing real sources cannot be examined in this manner for uniformity of emission. Some idea of the patchiness of the emission can still be obtained by comparing the east-west and north-south average profiles. Clearly, they should agree to within the noise, in any region either uniform or with strictly linear gradients of temperature. Differences significantly larger than noise indicate nonlinear gradients with a scale size comparable to the beamwidth. Since it is such nonlinear gradients that introduce errors in absorption measurements, a plot of the difference between the north-south and east-west averages should provide some indication of possible errors. We have included a plot of half the difference between the north-south and east-west averages [labeled $(NS - EW)/2$] in all of the figures showing the measurements on the various sources. It was felt that the deviations from zero on these plots would represent the magnitude of the errors to be expected in the absorption profiles because of emission variations. Judging from the cases of S8 and S9 in Figures 2 and 3, however, it would appear that the actual errors could easily be twice this value. Because of the likelihood of such errors and the low optical depths encountered off the galactic plane, we have chosen to label the single-dish profiles "on source-NSEW" instead of "absorption."

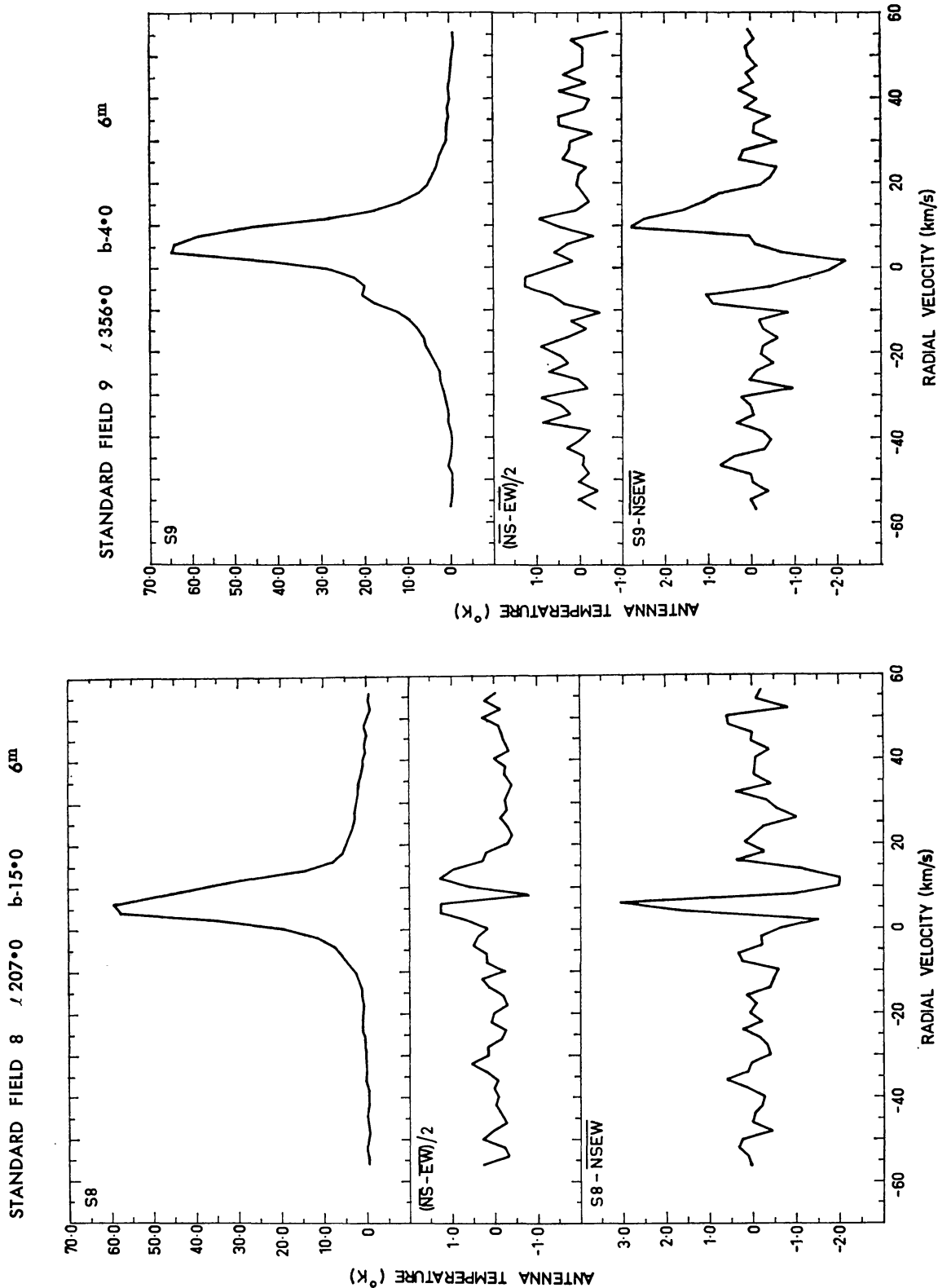


FIG. 2

FIG. 3

FIG. 2.—Measurements on the standard region S8 to determine uniformity of brightness. Single-dish absorption measurements on sources with $T_A \leq 5^\circ$ would have been rendered meaningless because of the emission irregularities. See text.

FIG. 3.—Measurements on the standard region S9 to determine uniformity of brightness. See legend to Fig. 2 and text.

III. CALIBRATION

Frequent calibration of the antenna temperature in all the single-dish measurements was carried out by means of a noise lamp switched in synchronism with the local-oscillator frequencies. Since both line and continuum measurements were calibrated with the same noise lamp, the optical-depth determinations are independent of the absolute value of the calibration signal. On the other hand, the calibration of brightness temperatures in terms of antenna temperatures does depend on its absolute value. For this reason the losses in the various components coupling the noise lamp to the receiver were carefully measured. With the feed system used for all the measurements reported in this paper, the ratio of flux to antenna temperature for point sources was found to be 1.66 f.u. per degree.

To determine the ratio of brightness temperature to antenna temperature for sources larger than the beam, a number of measurements were made of the signal from the lunar disk. The diameter of the Moon is such as to just completely include the main beam of the 64-m telescope when operating at 21 cm. The effective brightness temperature of the Moon at decimeter wavelengths has been given at $225^\circ \text{K} \pm 1.3^\circ \text{K}$ by Troitzky and Krotikov (1968). Adopting this value, we have determined the main-beam efficiency to be 80 percent. All of the emission profiles presented here have brightness temperatures equal to 1.25 times the antenna temperatures indicated in the figures, assuming, of course, that the distribution is uniform. As shown earlier, there are minor variations, even in regions like S8 and S9 which were thought to be uniform (see, e.g., Williams 1970). Nevertheless, any major discrepancy between our brightness-temperature scale and that of other observers should reveal itself by a comparison of their values for these two regions with the values in Figures 2 and 3 multiplied by 1.25. The profiles in these figures were obtained with rectangular filters of width 10 kHz spaced 9.5 kHz apart. The same filter bank was used for most of the observations reported in this paper. In three special cases we have made additional observations with filters of width 1 kHz spaced by their own width.

IV. RESULTS

Table 1 lists the 35 sources, together with their positions, galactic coordinates, and other names if any. Most of these sources have optical identifications; in column (7) we list the type of identification or other evidence for assuming an extragalactic nature for the source. The continuum antenna temperature is listed in column (8), and whether an observation was made with the single dish only or with the interferometer as well is indicated in column (9). Other absorption measurements on the source are indicated in column (10) by the initials of the observers. For 28 sources we include profiles, and the appropriate figure numbers for these are indicated in column (11). The single-dish profiles on the remaining seven sources were all so severely affected by emission variations as to render the observations meaningless as absorption measurements. An interferometer measurement on one of them was also of poor quality and has therefore been omitted.

The profiles themselves are presented in Figures 4 to 31. The radial velocities shown are with respect to the local standard of rest. All the sources were observed with filters of width 2.1 km s^{-1} (10 kHz). In the three cases where narrower filters (0.21 km s^{-1}) were also used the high-resolution profile follows the corresponding low-resolution one; the figures have the same number but are designated "a" and "b," respectively. The absorption profiles are always shown in the lowest part of a figure. Where absorption profiles were obtained by both single-dish and interferometer methods, the profiles have been superposed and the scales of optical depth made to agree. The corresponding emission profile obtained by averaging around the source position is always shown in the upper part of a figure labeled NSEW. The left-hand ordinate in all cases is antenna temperature.

TABLE 1
SOURCES OBSERVED FOR H I ABSORPTION

SOURCE (1)	OTHER NAMES (2)	POSITION (1950.00)		GALACTIC COORDINATES		OPTICAL IDENTI- FICATION OR SIZE (7)	T_A (° K) (8)	TYPE OF MEASURE- MENT (9)	OTHER OBSERVATIONS* (10)	FIGURE NUMBER (11)
		R.A. (3)	Decl. (4)	l (5)	b (6)					
3C 33.....	...	01 ^h 06 ^m 14 ^s 0	13° 14' 1	129.5	-49.3	D	8.6	SD	HTC	4
CTA 21.....	...	03 16 09.0	16 17.7	166.6	-33.6	Scint.	4.8	SD	HTC	†
For A (a).....	...	03 19 39.0	-37 19.0	240.1	-56.9	So	24.0	SD		5
3C 98.....	...	03 56 15.0	10 17.7	179.9	-31.0	E	7.0	SD I	HTC, TKM	6
0408-65.....	MSH 04-62	04 08 06.0	-65 49.0	278.6	-40.9	QSO	8.7	SD		7
0410-75.....	MSH 04-71	04 10 11.0	-75 15.3	289.0	-36.1	<0'.4	7.4	SD I		8
3C 138.....	...	05 18 19.0	16 35.7	187.4	-11.3	QSO	6.6	SD I	HTC	9
Pic A.....	MSH 05-43	05 18 24.0	-45 49.8	251.6	-34.6	D	35.0	SD	HTC, BGC	10
0521-36.....	MSH 05-36	05 21 14.0	-36 30.0	240.6	-32.7	N	10.4	SD	HTC	†
0531+19.....	...	05 31 48.0	19 25.5	186.8	-7.1	E	3.6	SD I	HTC	11
30 Dor.....	...	05 39 00.0	-69 07.0	279.5	-31.7	LMC	22.0	SD		12
3C 161.....	MSH 06-04	06 24 43.0	-05 51.1	215.4	-8.1	Scint.	11.2	SD I	HTC, TKM	13
0634-20.....	MSH 06-210	06 34 23.0	-20 34.0	229.9	-12.4	E	3.5	SD	HTC	14
0741-06.....	...	07 41 55.0	-06 22.3	224.9	+08.6	Scint.	4.6	SD		†
Hya A.....	3C 218	09 15 41.0	06 05.6	242.9	+25.1	D	25.2	SD I	HTC, BGC	15
3C 270.....	MSH 12+05	12 16 52.0	02 19.1	281.8	+67.4	E	10.2	SD		16
3C 273.....	MSH 12+08	12 26 34.0	02 19.1	290.0	+64.4	QSO	26.6	SD	HTC, DRW	17
M87.....	3C 274	12 28 17.0	12 39.4	283.8	+74.5	E	128.1	SD	BGC, CHTV	18
NGC 4945.....	...	13 02 32.0	-49 12.1	305.3	+13.3	Sc	3.9	SD		†
Cen A.....	NGC 5128	13 22 24.0	-42 45.0	309.5	+19.4	So	152.0	SD I	HTC, BGC	19
3C 327.....	...	15 59 57.0	02 06.3	12.5	+37.9	D	5.2	SD I	HTC	20
1610-60.....	MSH 16-61	16 11 15.0	-60 59.0	325.3	-7.2	E	25.6	SD I		21
Her A.....	3C 348	16 48 42.0	05 04.5	23.1	+28.9	D	28.5	SD I	HTC, TKM, BGC	22
3C 353.....	MSH 17-06	17 17 56.0	-00 55.4	21.2	+19.6	D	31.3	SD I	HTC, TKM, BGC	23
1733-56.....	...	17 33 20.0	-56 31.7	335.4	-13.0	Double	4.4	SD		24
1814-63.....	MSH 18-61	18 14 49.0	-63 47.0	330.9	-20.8	Scint.	7.2	SD		25
1827-36.....	...	18 27 37.0	-36 04.8	358.3	-11.8	Scint.	3.4	SD	HTC	26
3C 386.....	...	18 36 13.0	17 09.2	47.0	+10.6	D	4.0	SD	HTC	†
1932-46.....	MSH 19-46	19 32 20.0	-46 28.2	352.2	-26.7	Scint.	7.0	SD I	HTC	†
1934-63.....	...	19 34 45.0	-63 49.3	332.8	-29.4	G	9.0	SD		†
3C 409.....	...	20 12 18.0	23 25.9	63.4	-6.1	<0'.3	7.6	SD I	HTC	27
2104-25.....	MSH 21-21	21 04 23.0	-25 39.0	21.4	-40.2	E	6.8	SD	HTC	28
3C 433.....	...	21 21 31.0	24 51.9	74.5	-17.7	D	7.3	SD I	HTC	29
2152-69.....	MSH 21-64	21 52 58.0	-69 55.8	321.3	-40.7	D	17.0	SD		30
3C 454.3.....	...	22 51 28.0	15 53.4	86.1	-38.2	QSO	8.0	SD I	HTC	31

* Abbreviations are: BGC, Clark (1965); DRW, Williams (1965); CHTV, Colvin *et al.* (1970); TKM, T. K. Menon (private communication); HTC, Hughes, Thompson, and Colvin (1971).
† Single-dish observations rendered useless by severe emission variations.

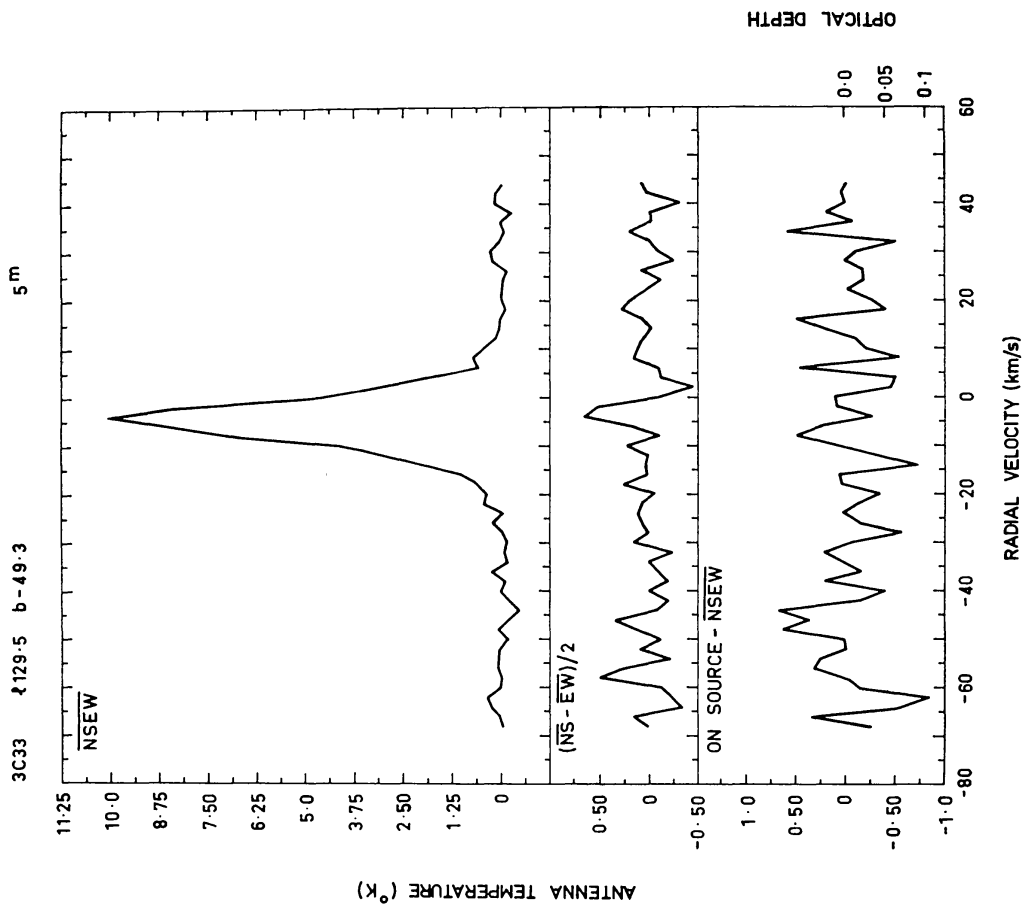


FIG. 4

FIG. 4.—3C 33.

FIG. 5.—The continuum distribution of this double source made it possible to obtain only two symmetrically spaced references. The emission temperature varied significantly between these positions as seen in the upper figure.

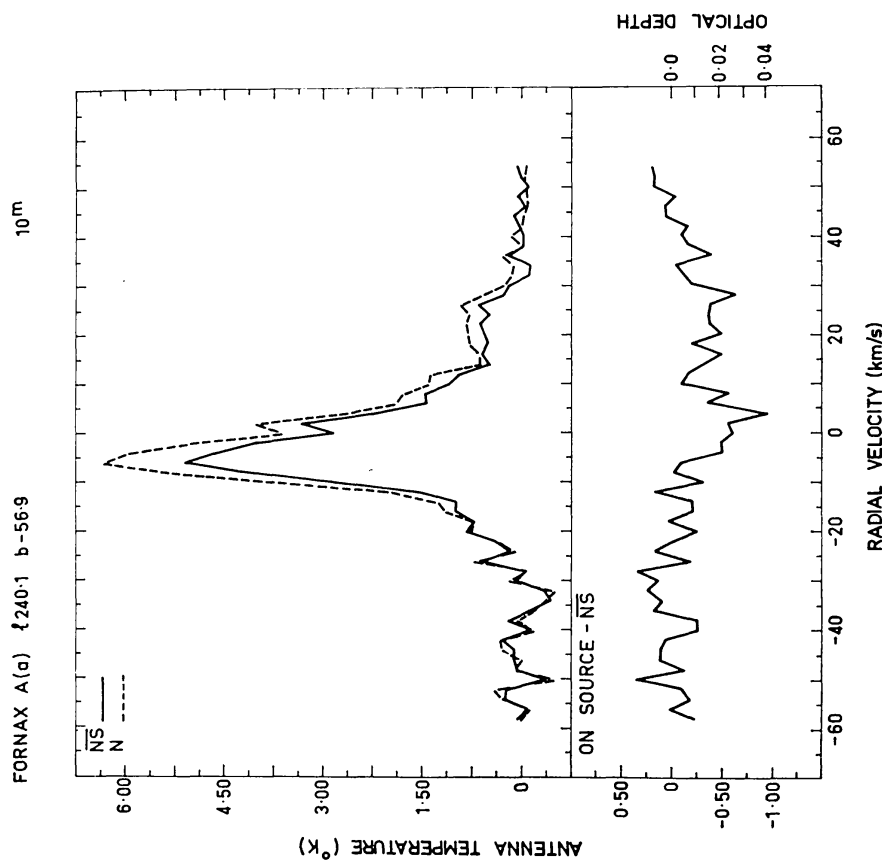


FIG. 5

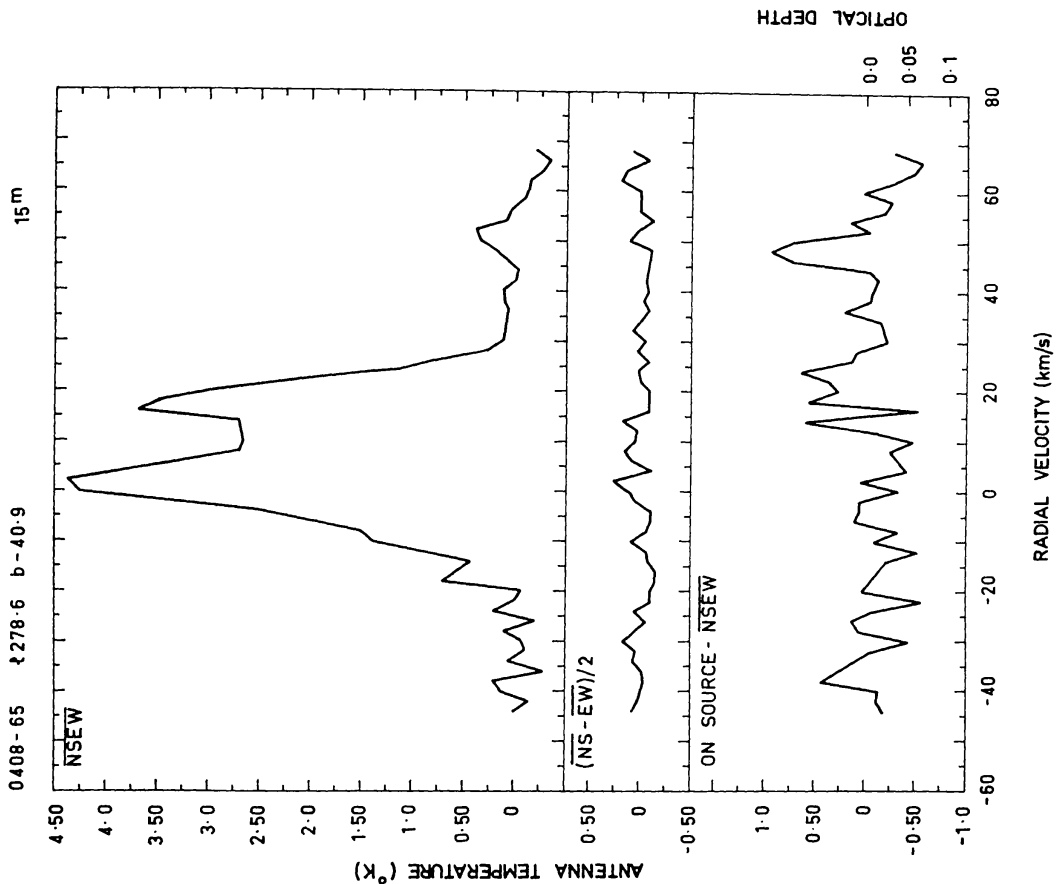


FIG. 7

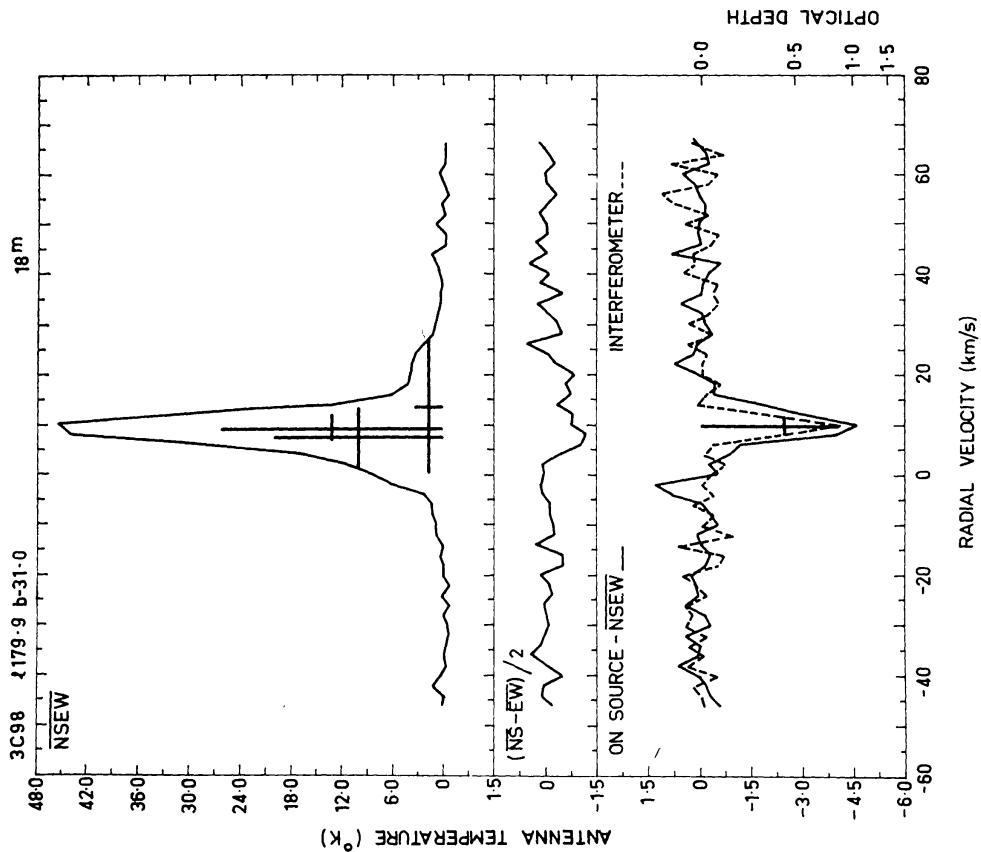


FIG. 6

FIG. 6.—3C 98.
FIG. 7.—0408—65.

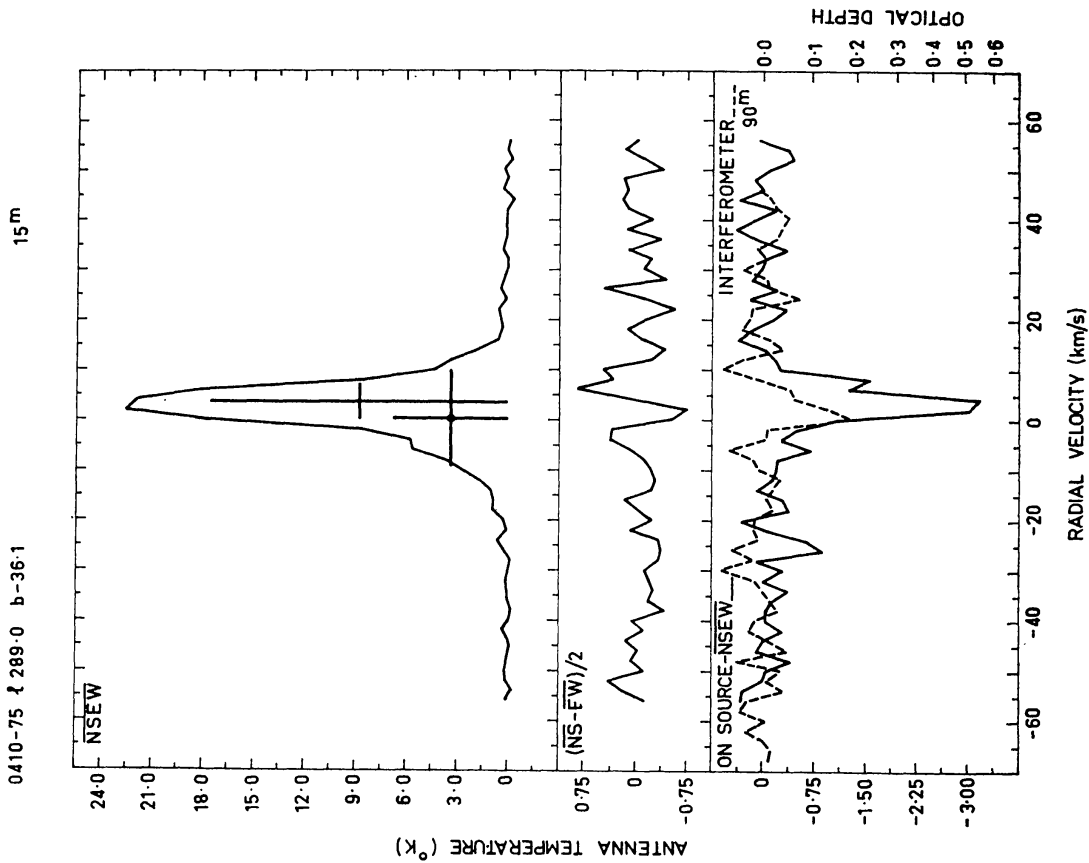


FIG. 8

FIG. 8.—0410-75.
FIG. 9.—3C 138.

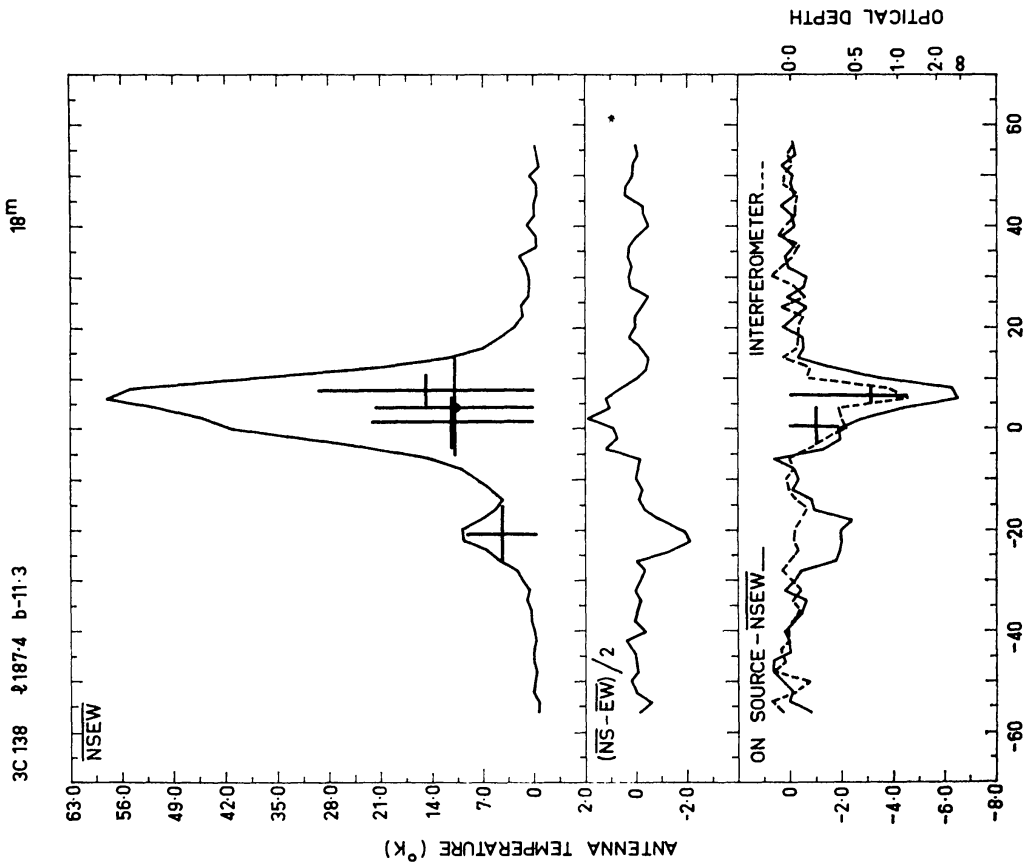


FIG. 9

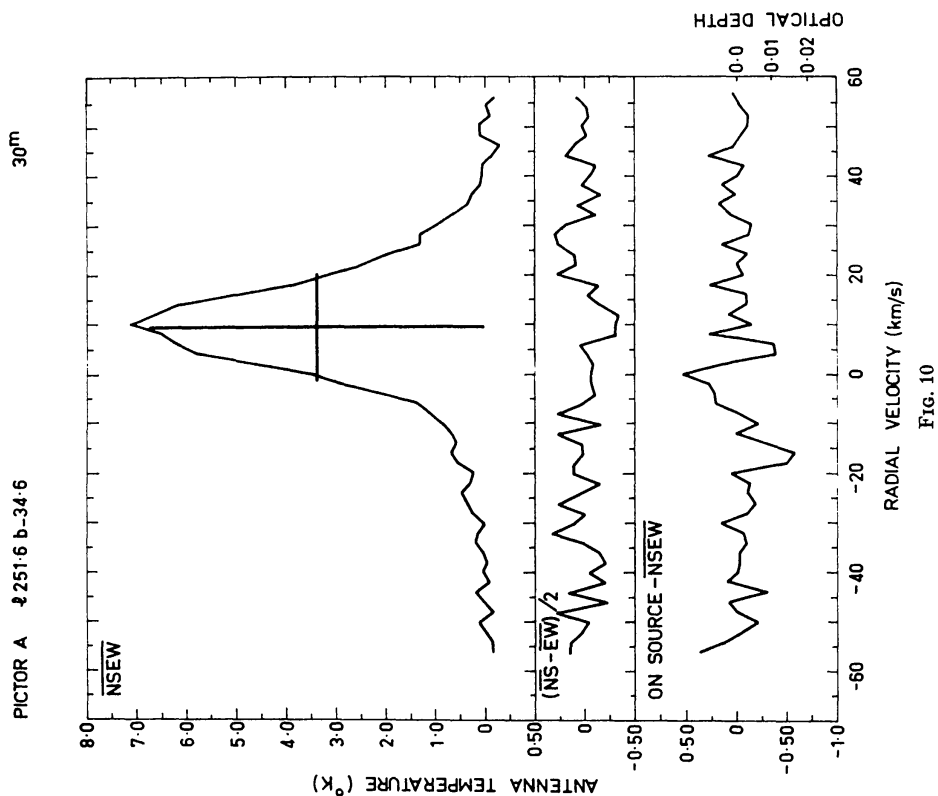
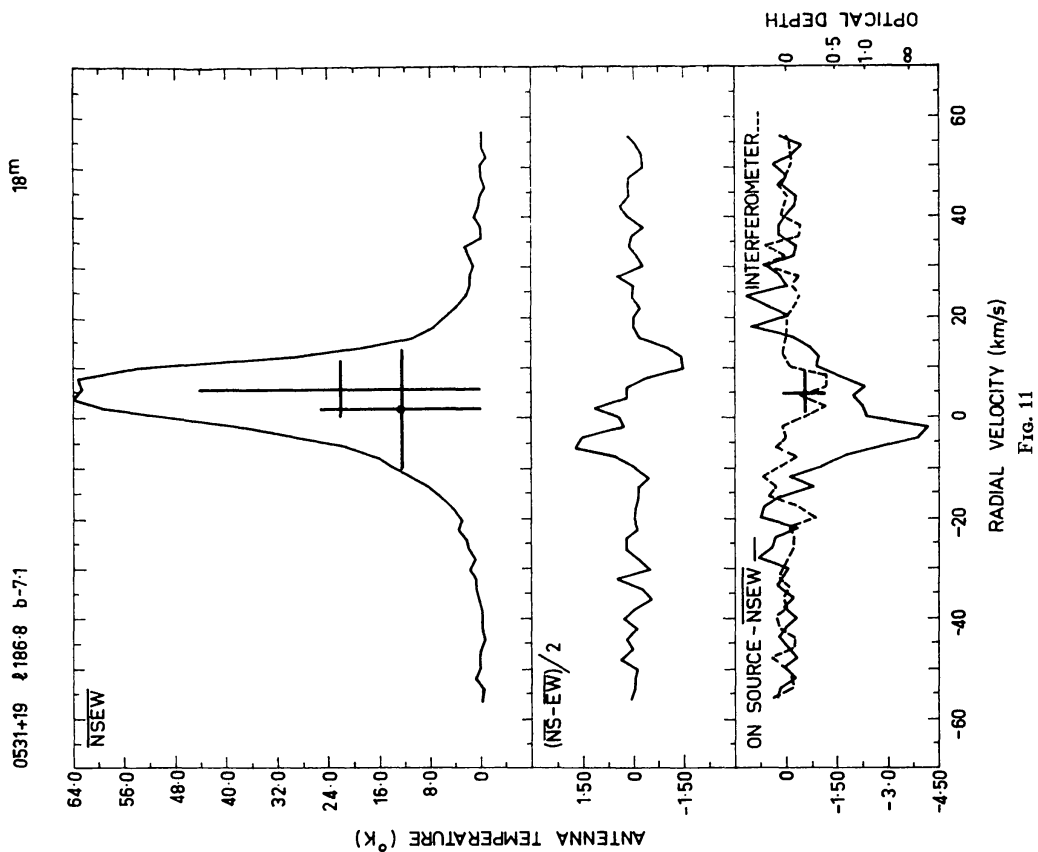


FIG. 10.—Pic A.
FIG. 11.—0531+19.

30 DORADUS λ 279 $\cdot$ 5 b-31 $\cdot$ 7 30m 3C 161 λ 215 $\cdot$ 4 b-8 $\cdot$ 1 18m

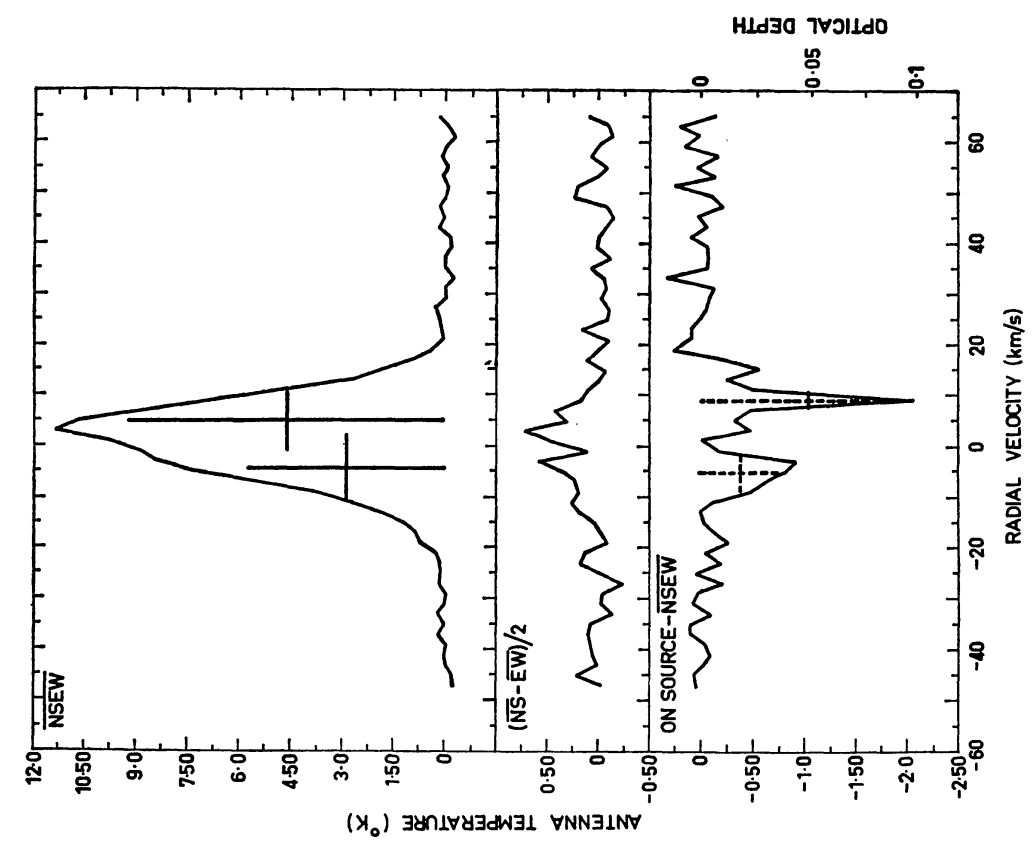


FIG. 12

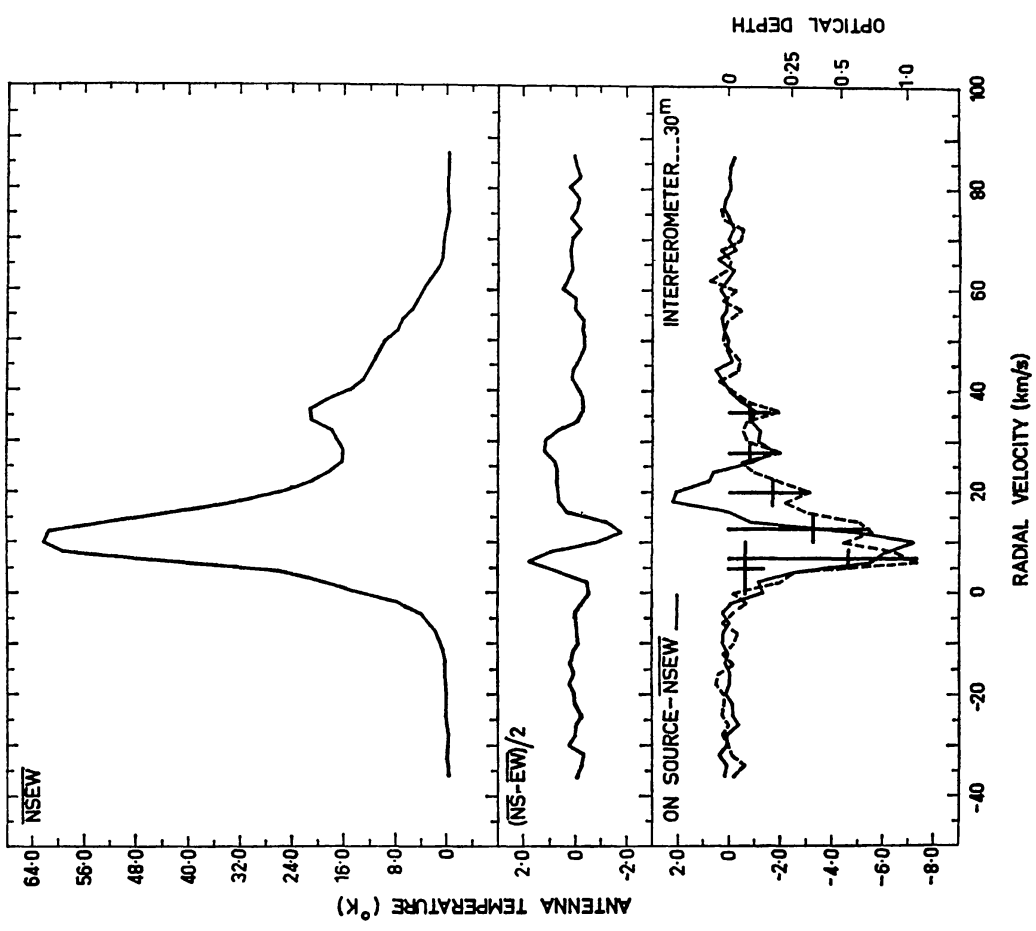


FIG. 13

Fig. 12.—Single-dish measurements on 30 Dor. The lack of correspondence between the narrow absorption feature and the stronger emission component suggests either that the absorption feature is spurious or that the emission profile has more components closely blended together.

Fig. 13.—3C 161.

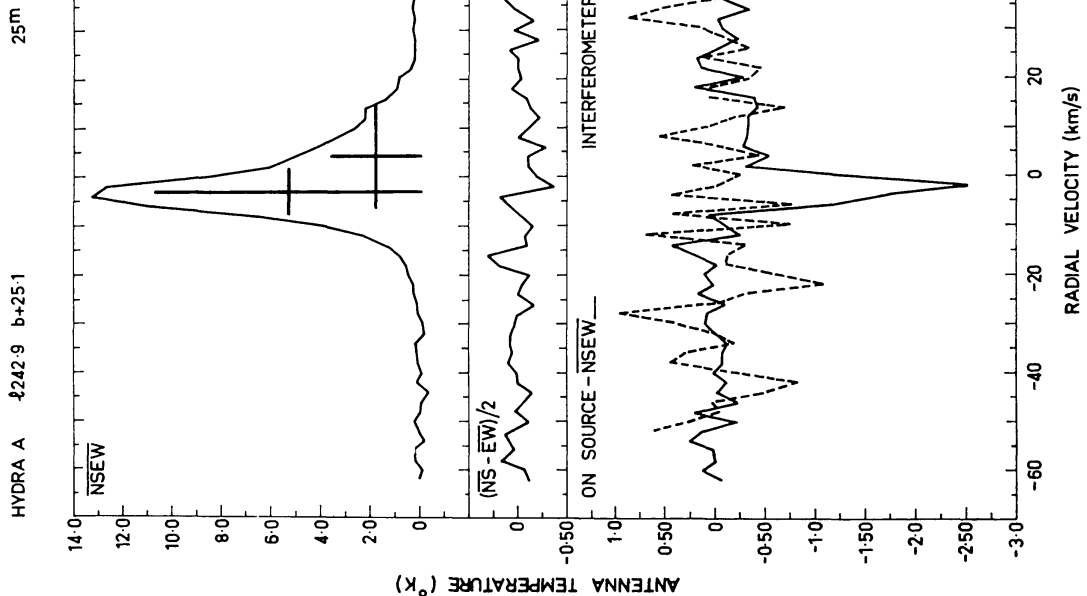


FIG. 15

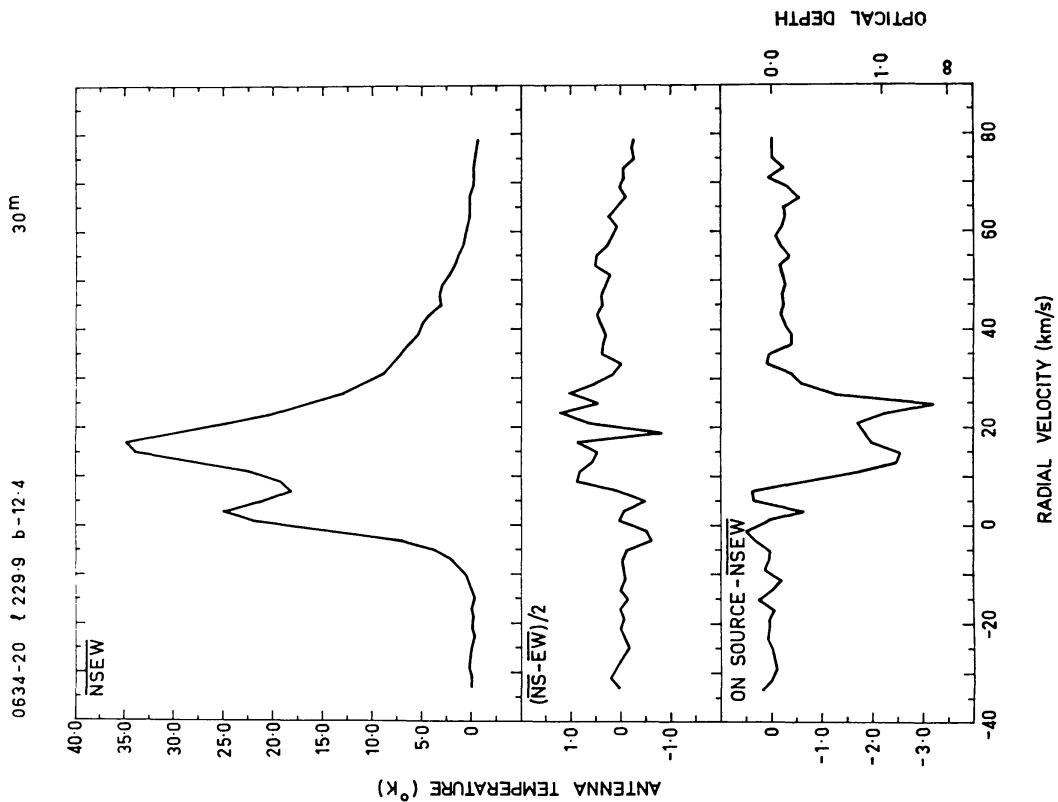


FIG. 14

FIG. 14.—0634—20.
FIG. 15.—Hya A.

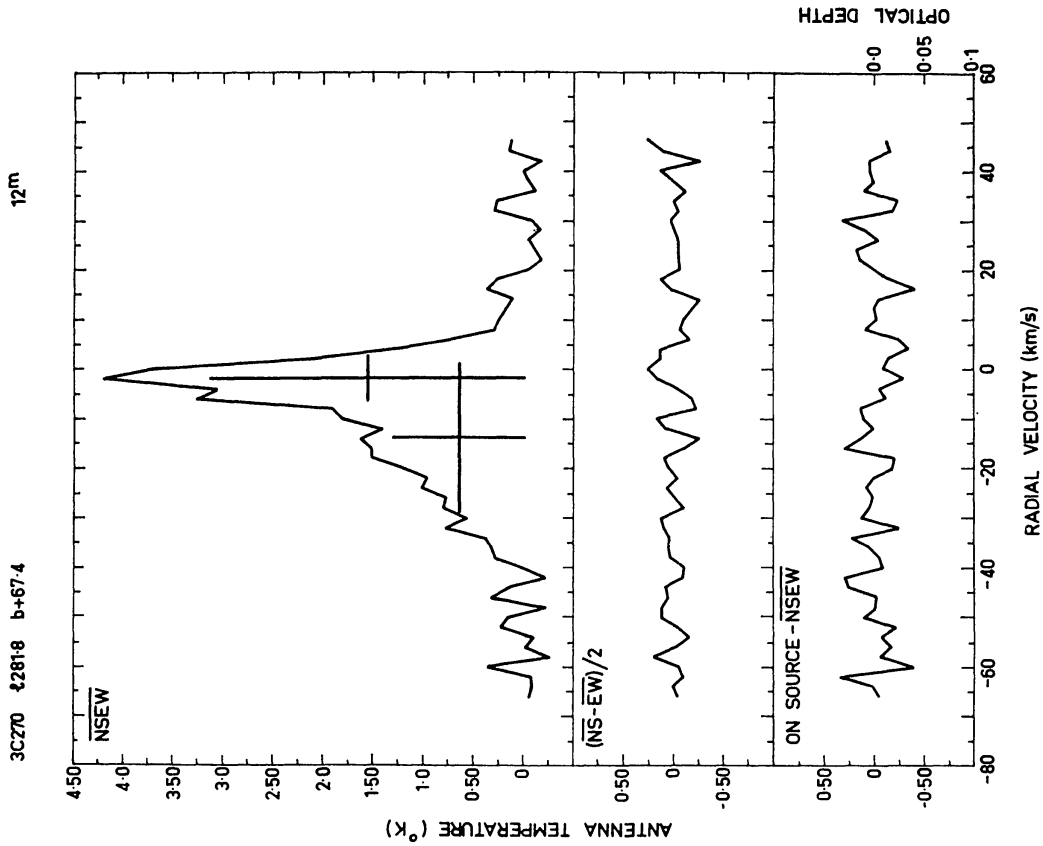


Fig. 16

FIG. 16.—3C 270.
FIG. 17.—3C 273.

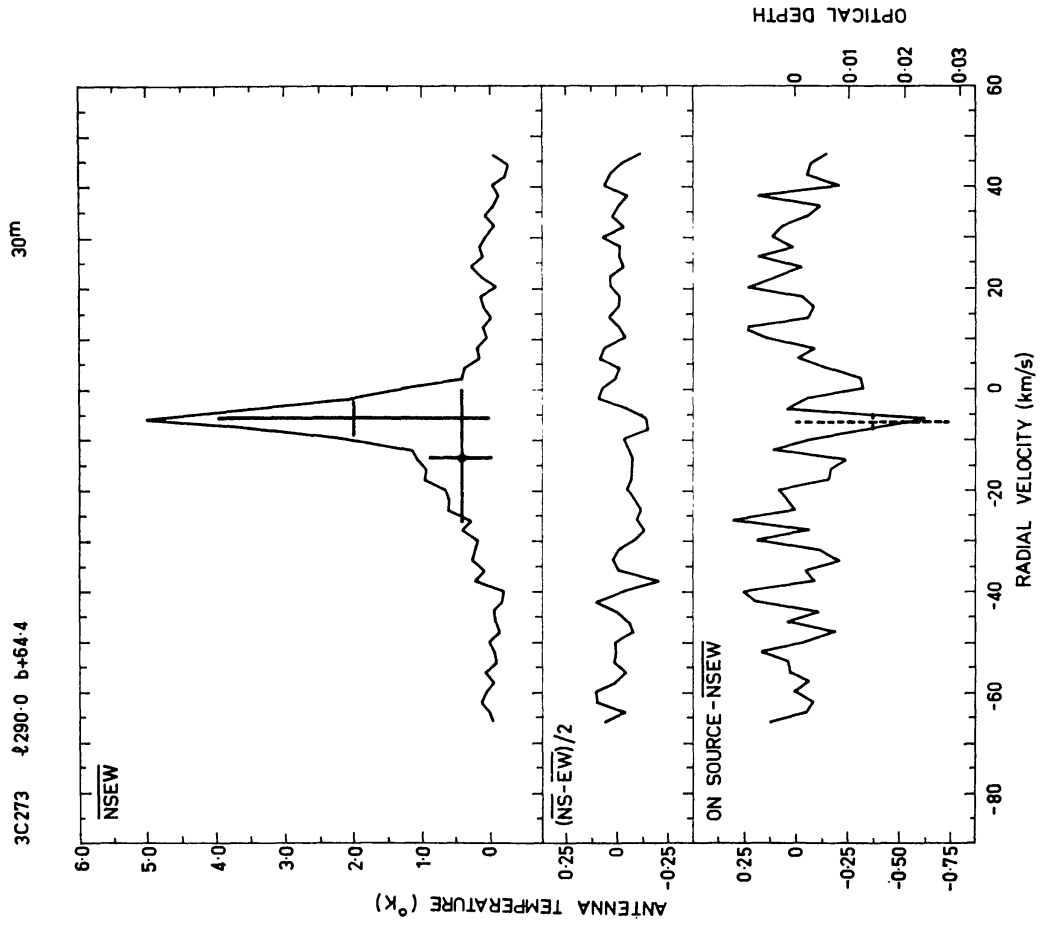


Fig. 17

CENT A $\lambda 309.5$ b+19.4

12^m

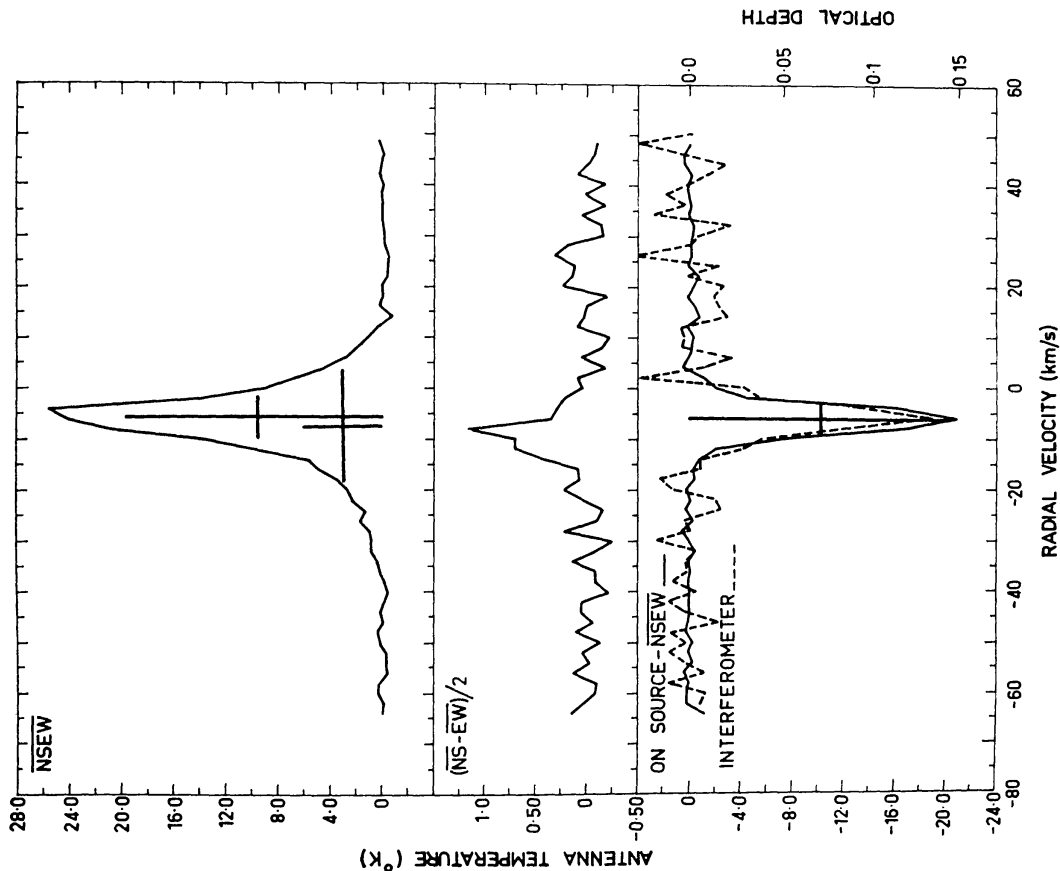


FIG. 19a

M87 $\lambda 283.3$ b+74.5

30^m

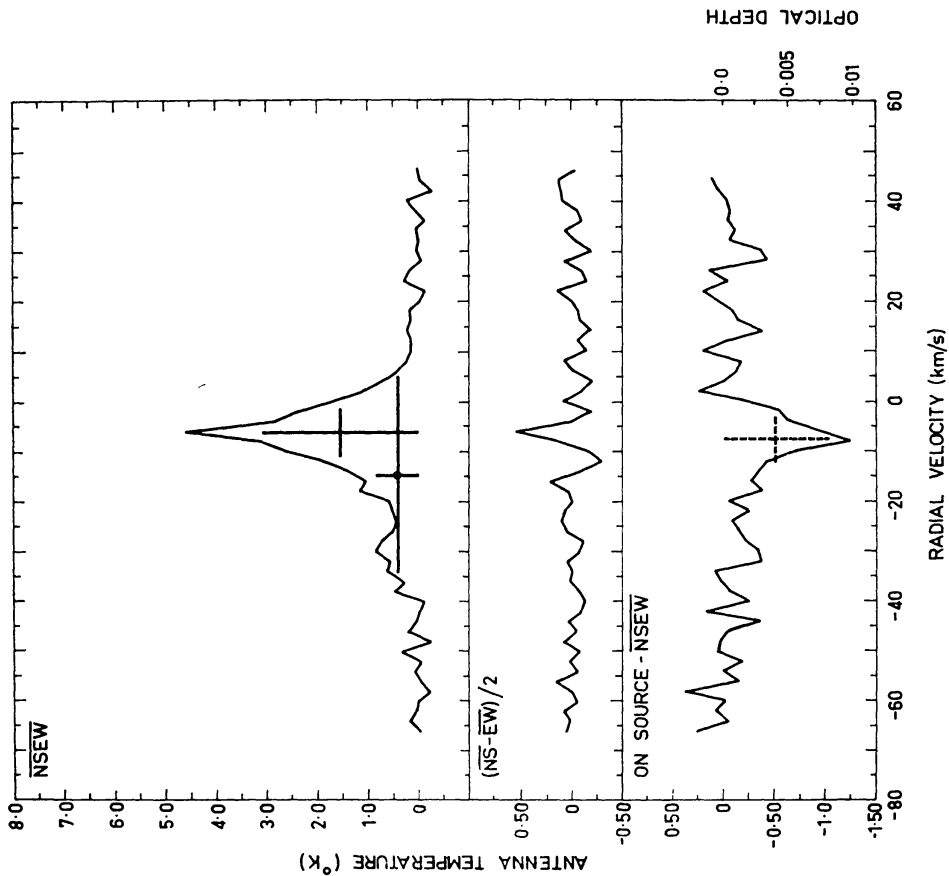


FIG. 18

FIG. 18.—M87.

FIG. 19a.—Cen A.

15^m

CENTAURUS A J 309.5 b+19.4

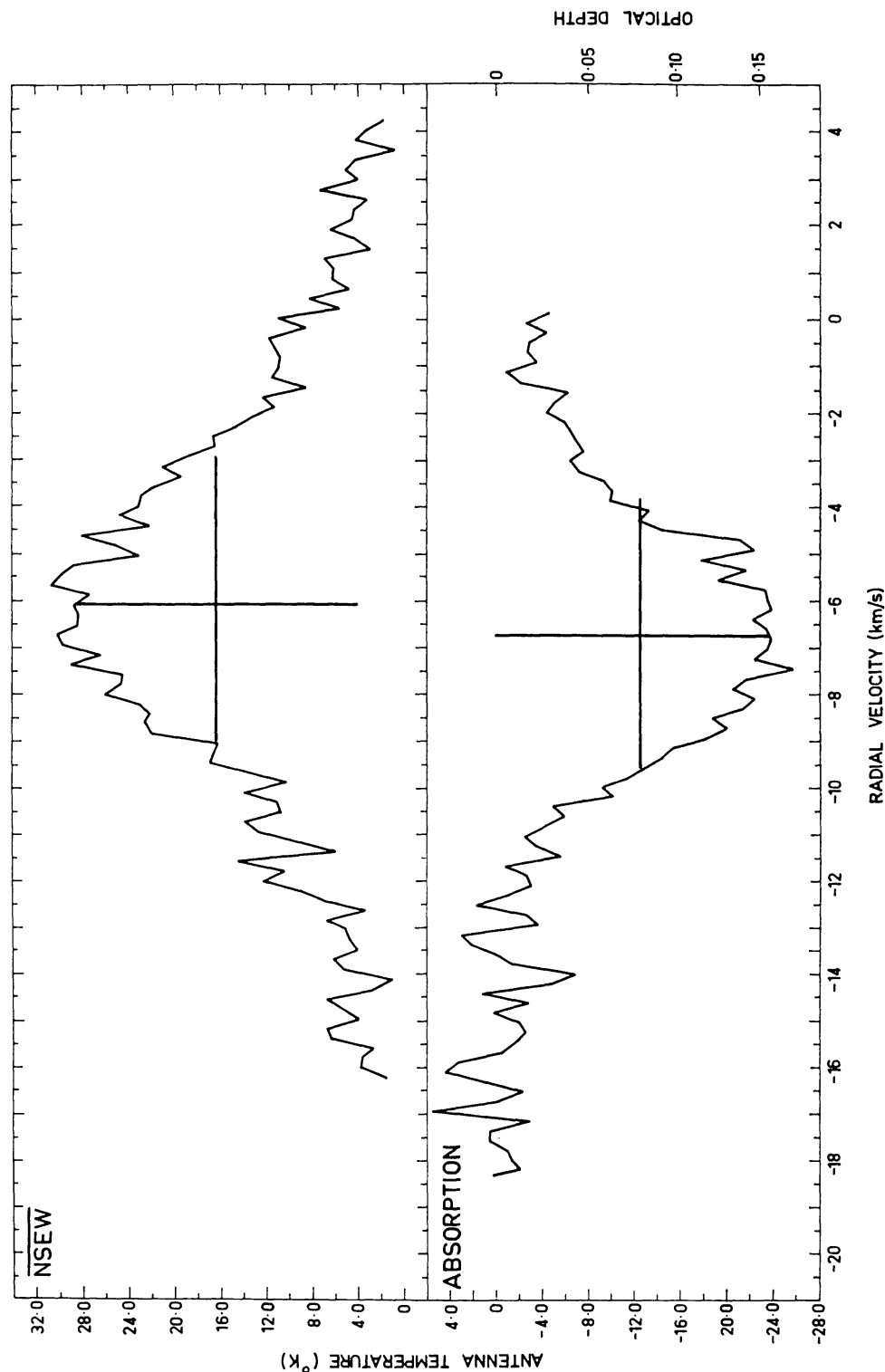


FIG. 19b.—Single-dish measurements with 1-kHz filters on Cen A. Only the narrow component of the emission in Fig. 19a is shown here in the upper figure. There is a faint suggestion in the incomplete absorption profile (*lower*) and also in Fig. 19a of a secondary absorption feature at -2 km s^{-1} .

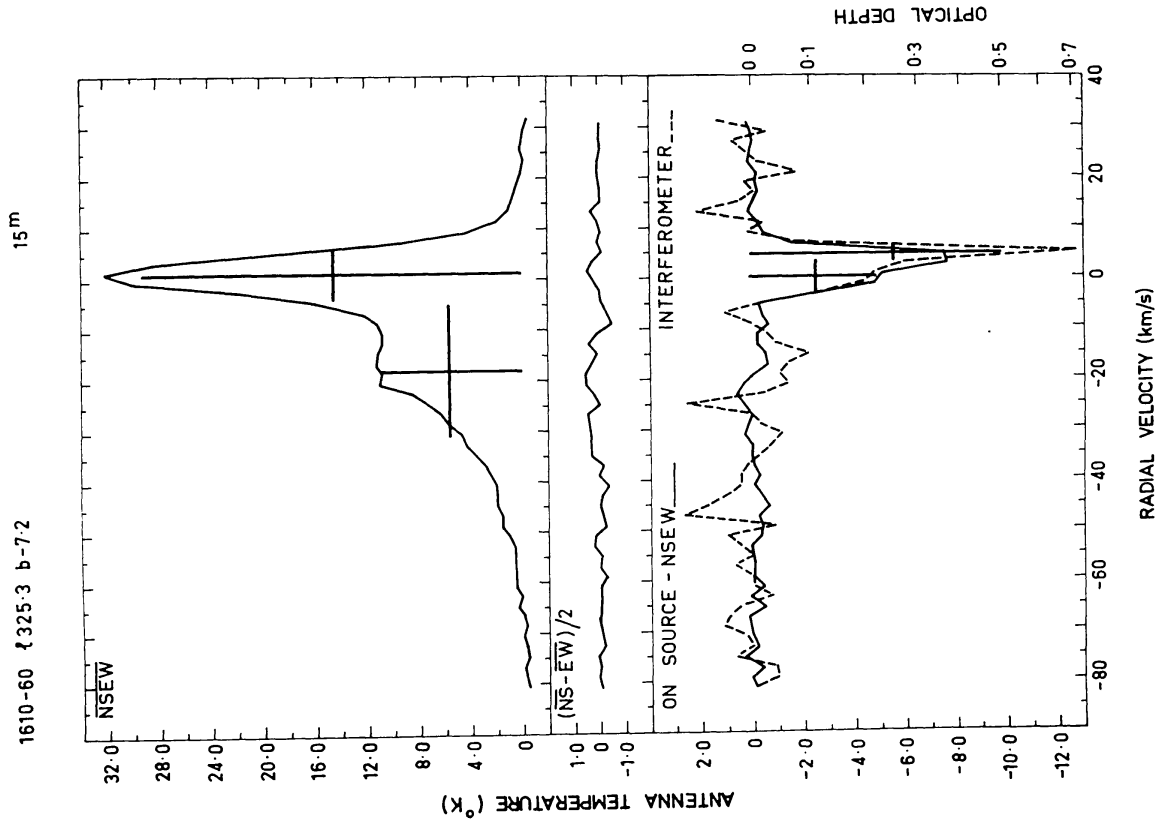


Fig. 21a

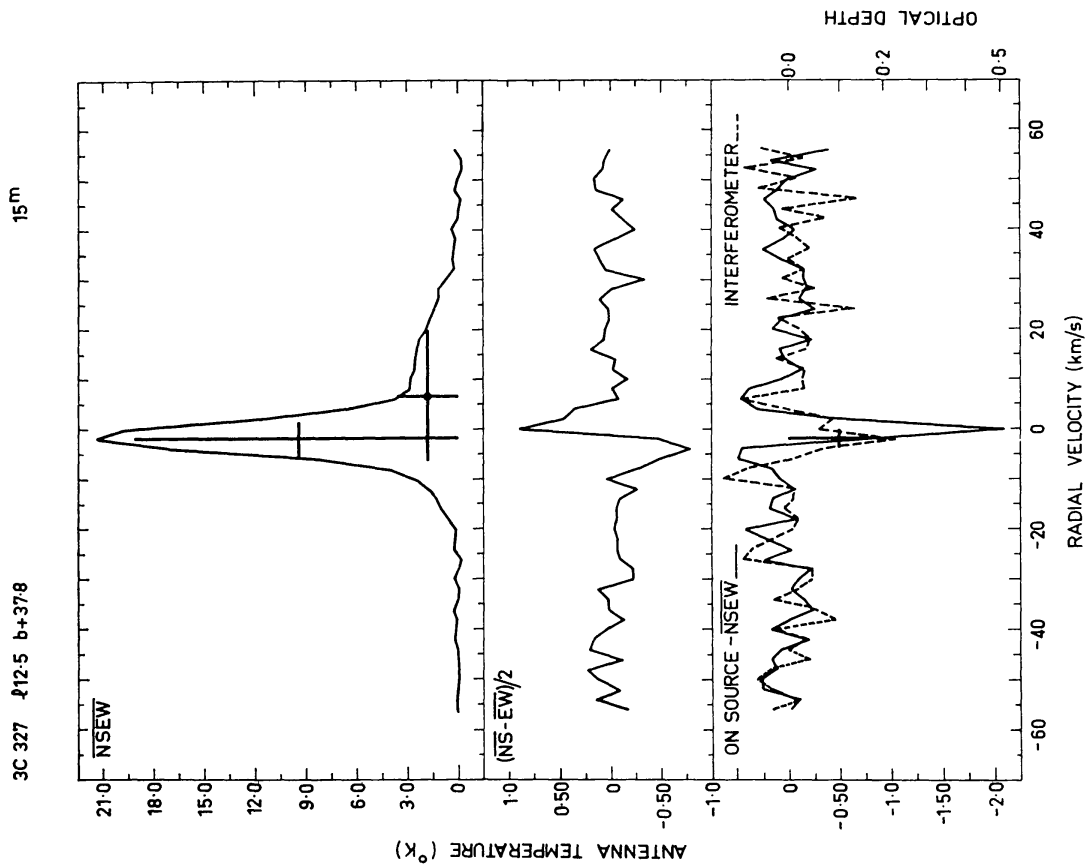


Fig. 20

Fig. 20.—3C 327.
Fig. 21a.—1610-60.

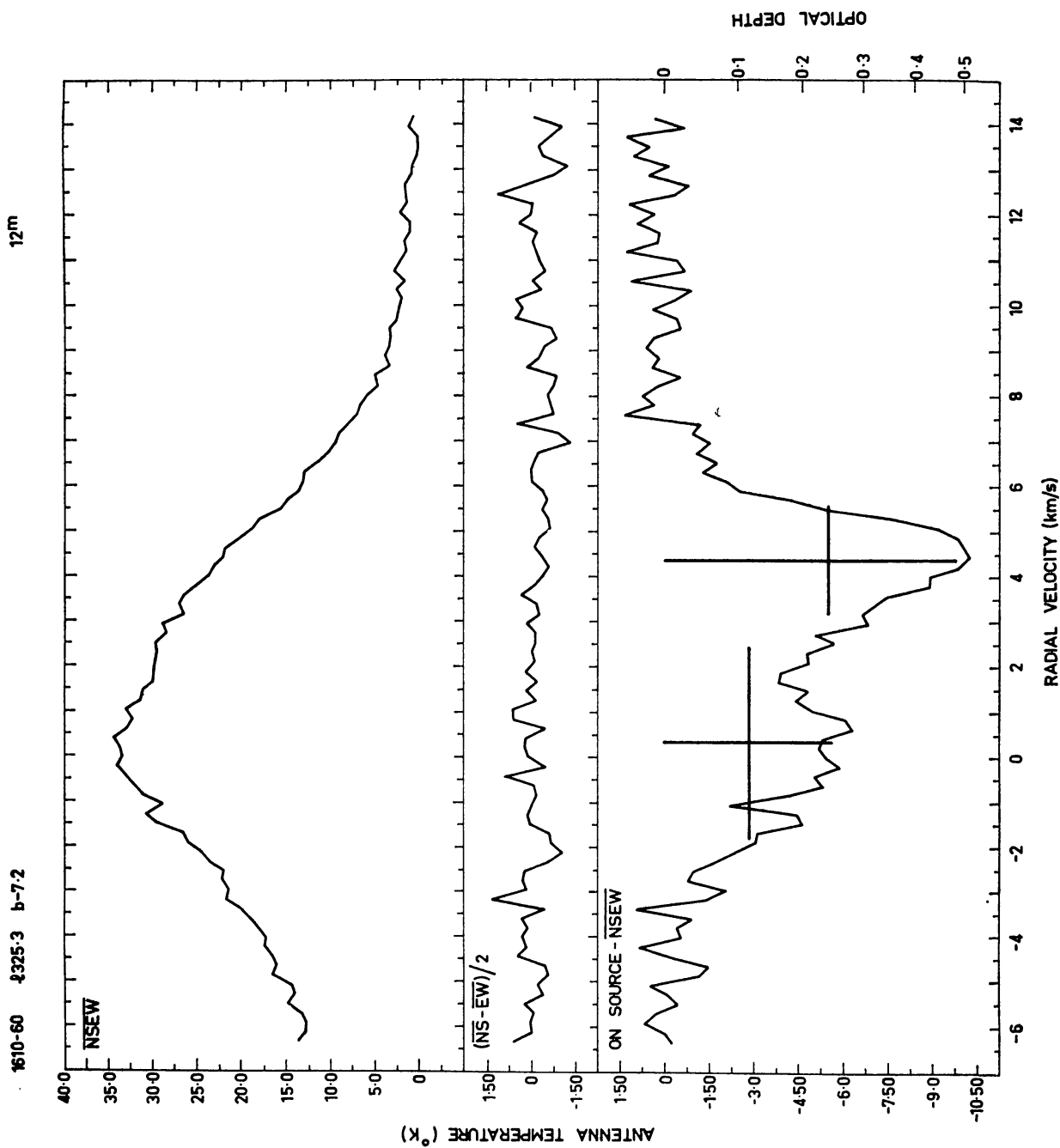


FIG. 21*b*.—Single-dish measurements with 1-kHz filters on 1610—60. The resolution of the emission profile (*upper*) into Gaussians was complicated by the presence of the wing of the wide component (Fig. 21*a*). It is nevertheless apparent that the absorption component at 4.5 km s⁻¹ (*lower*) has a much wider emission counterpart.

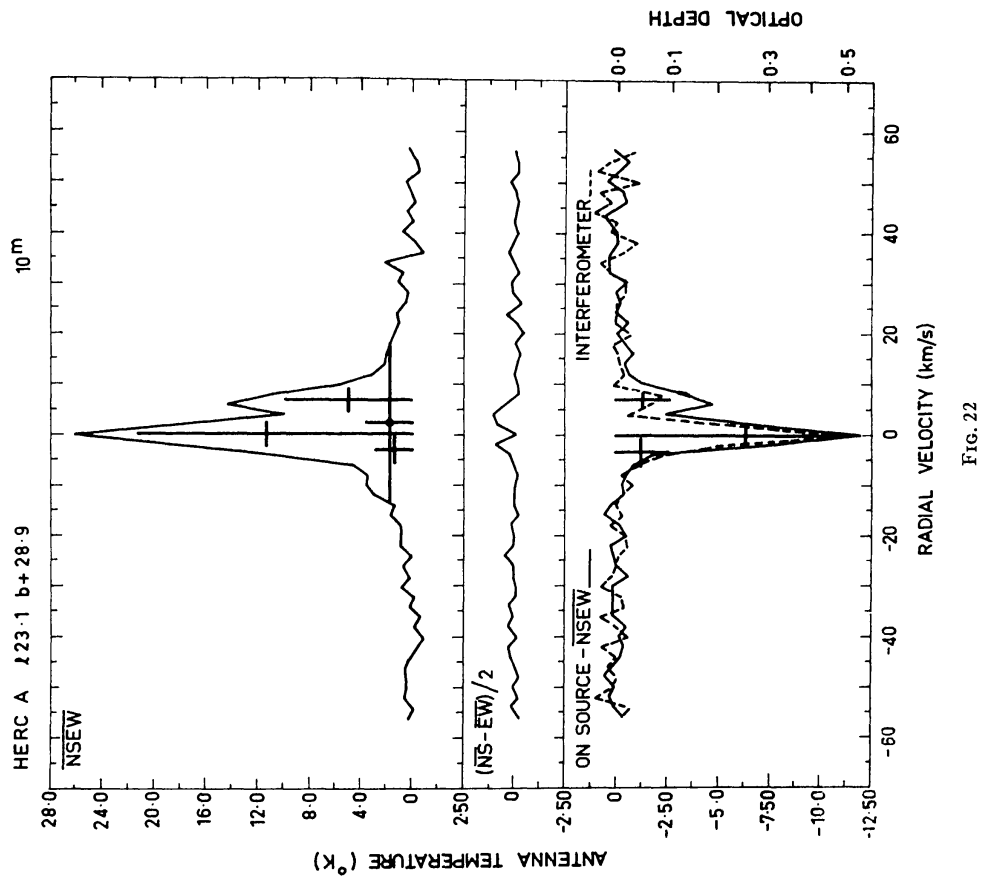
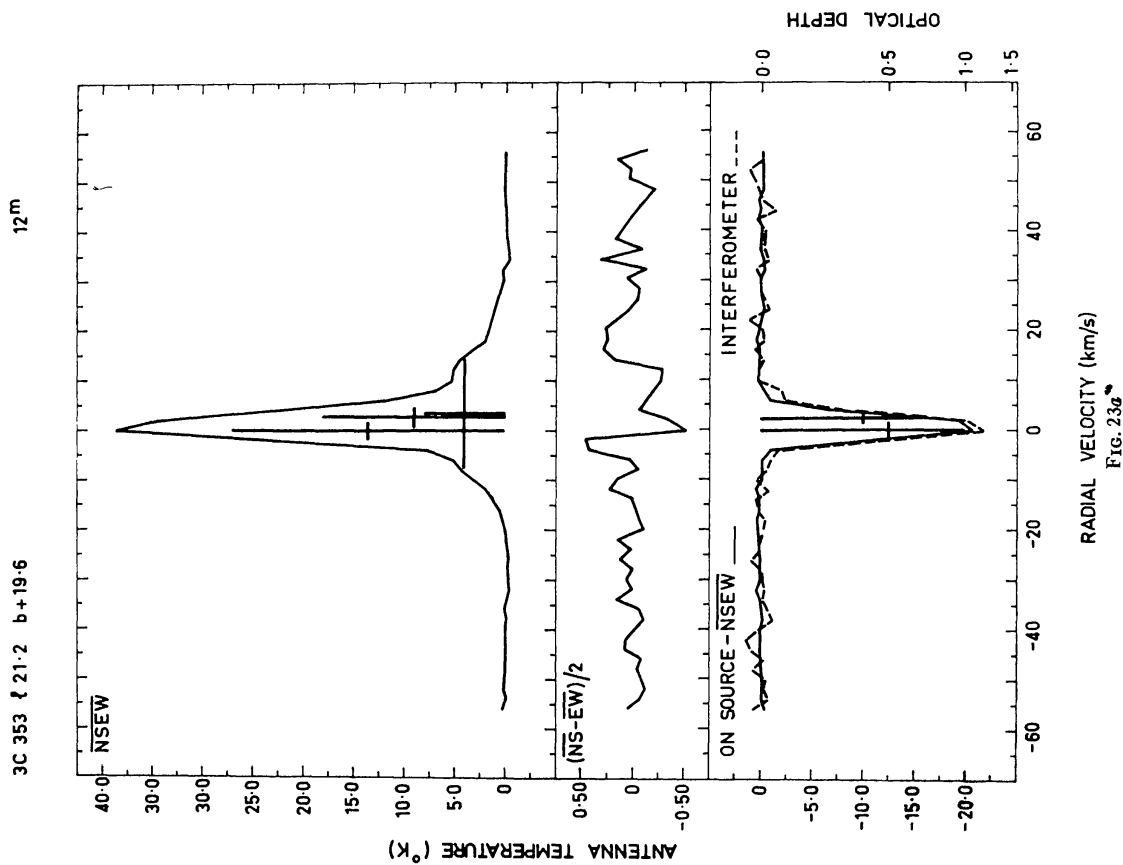


FIG. 22.—Her A.
FIG. 23a.—3C 353.

3C 353 λ 21.2 b+19.6

30^m

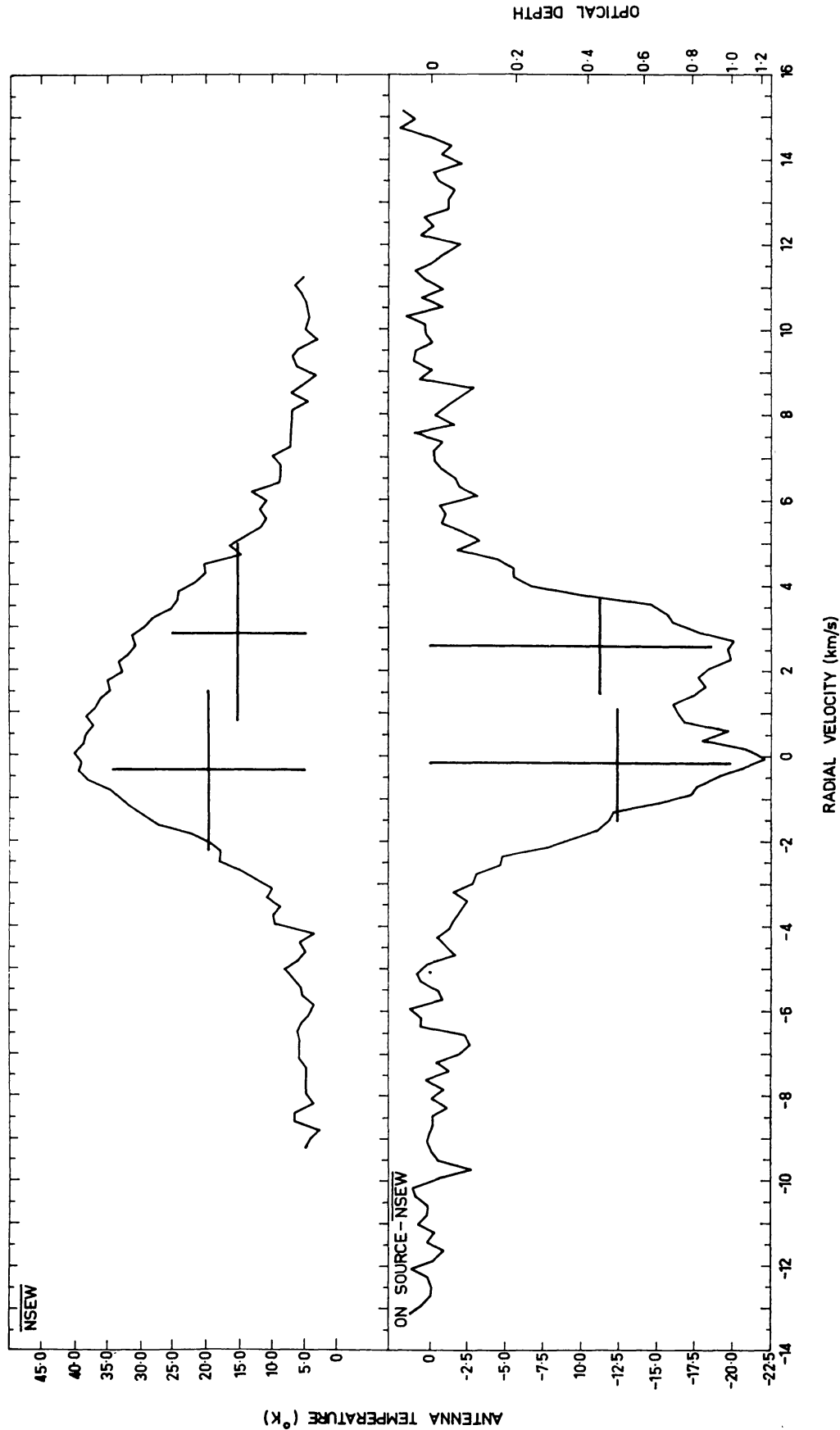


FIG. 23*b*.—Single-dish measurements with 1 kHz filters on 3C 353. The emission and absorption features which showed only marginal signs of splitting in Fig. 23*a* (10-kHz filters) are clearly separated here. The emission components (*upper*) are significantly wider than their absorption counterparts (*lower*). See text for discussion.

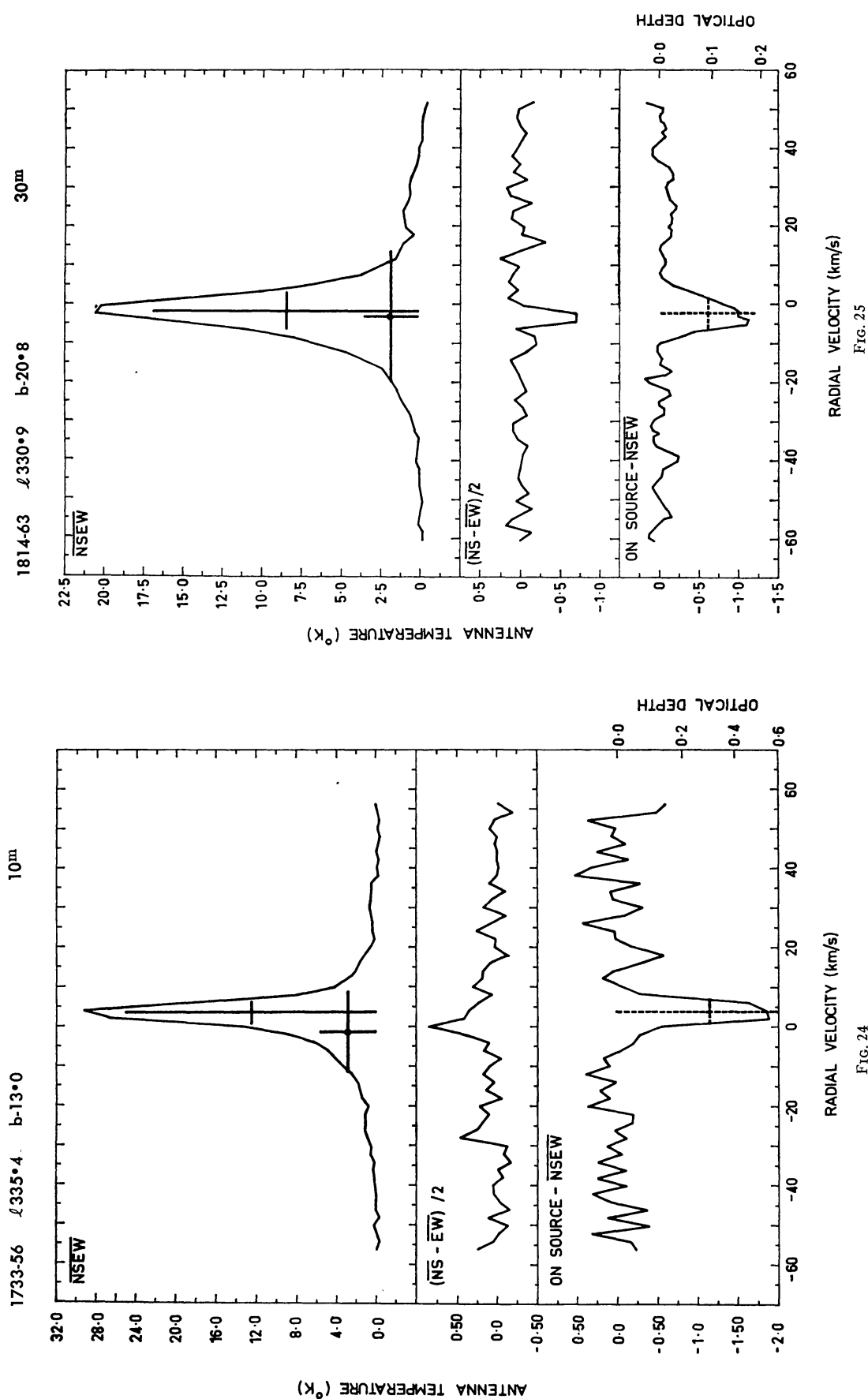


FIG. 24

FIG. 25

FIG. 24.—1733—56.
FIG. 25.—1814—63.

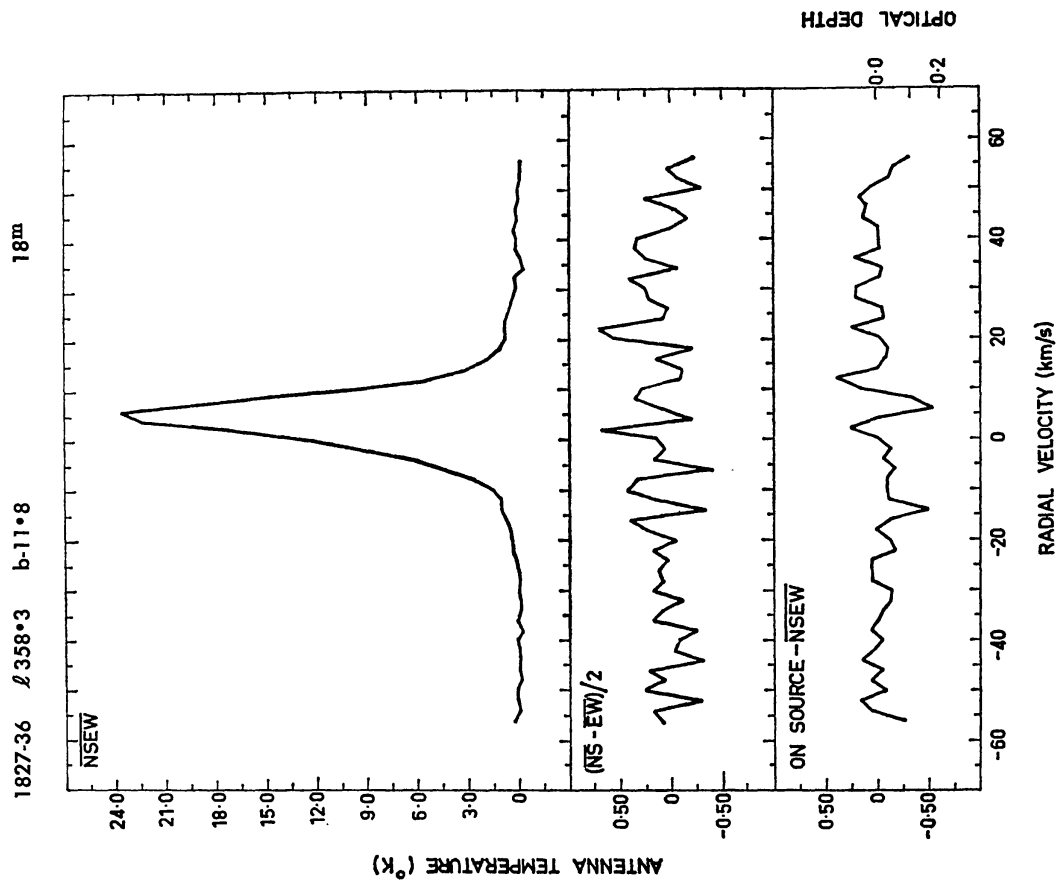


FIG. 26

FIG. 26.—1827—36.
FIG. 27.—3C 409.

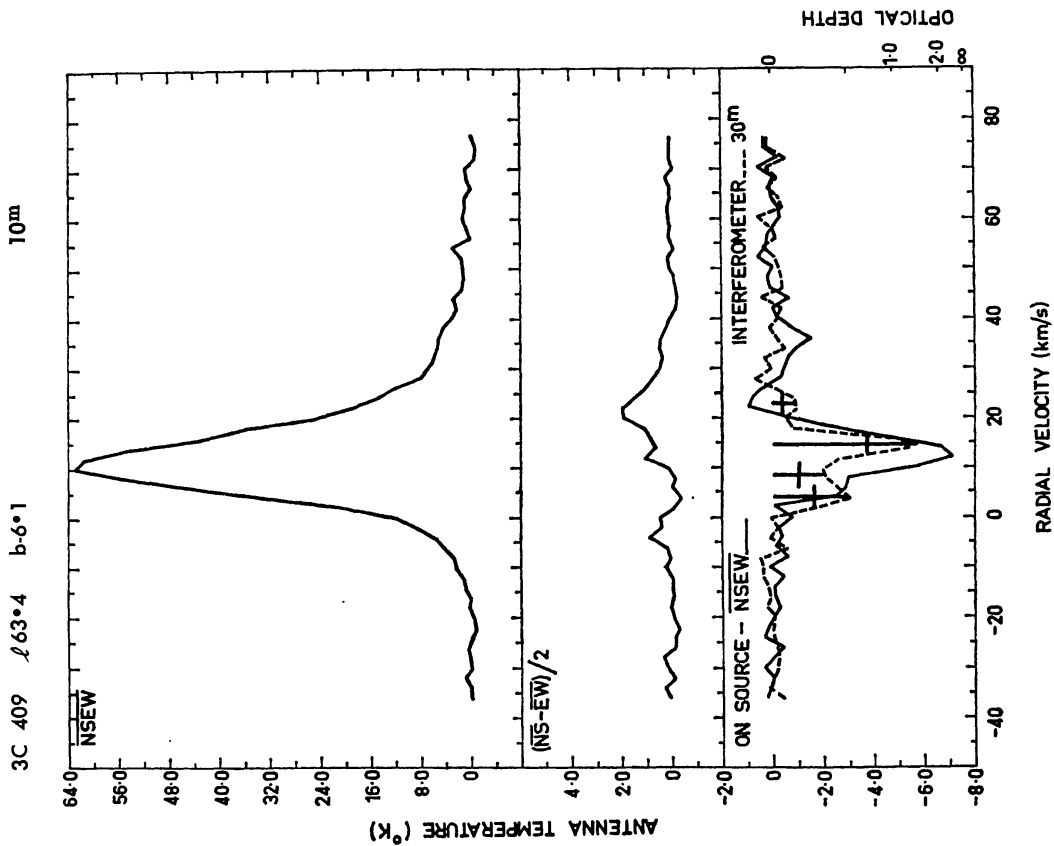


FIG. 27

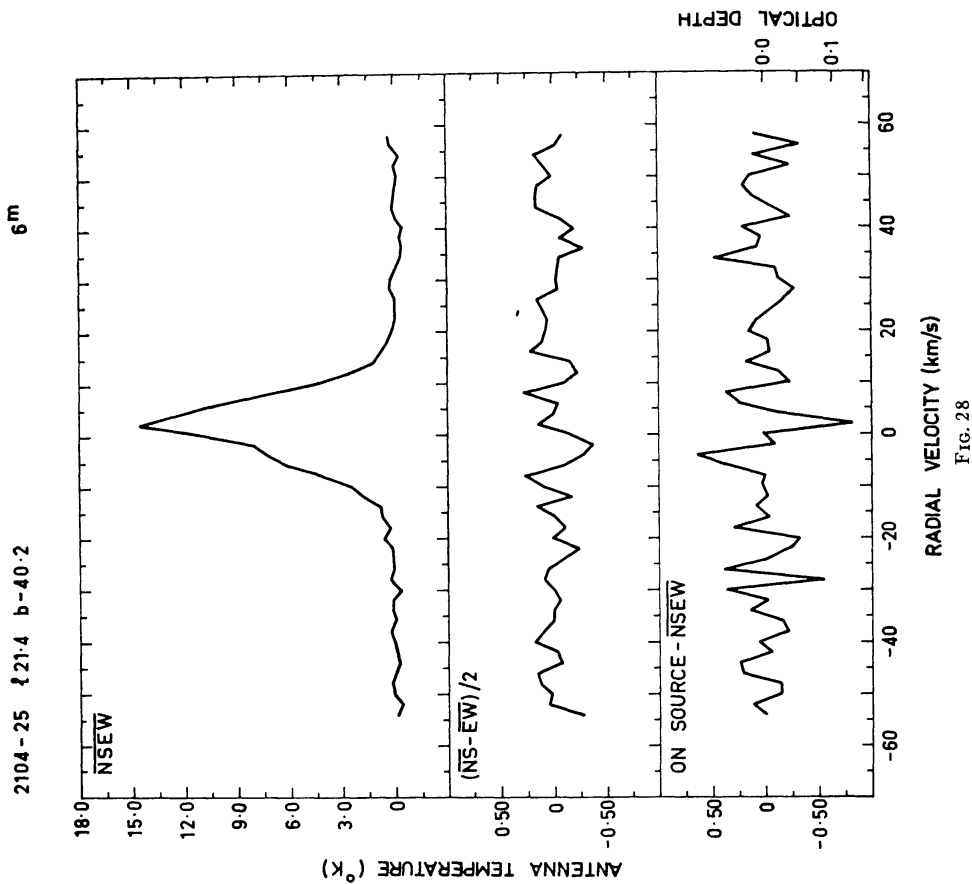
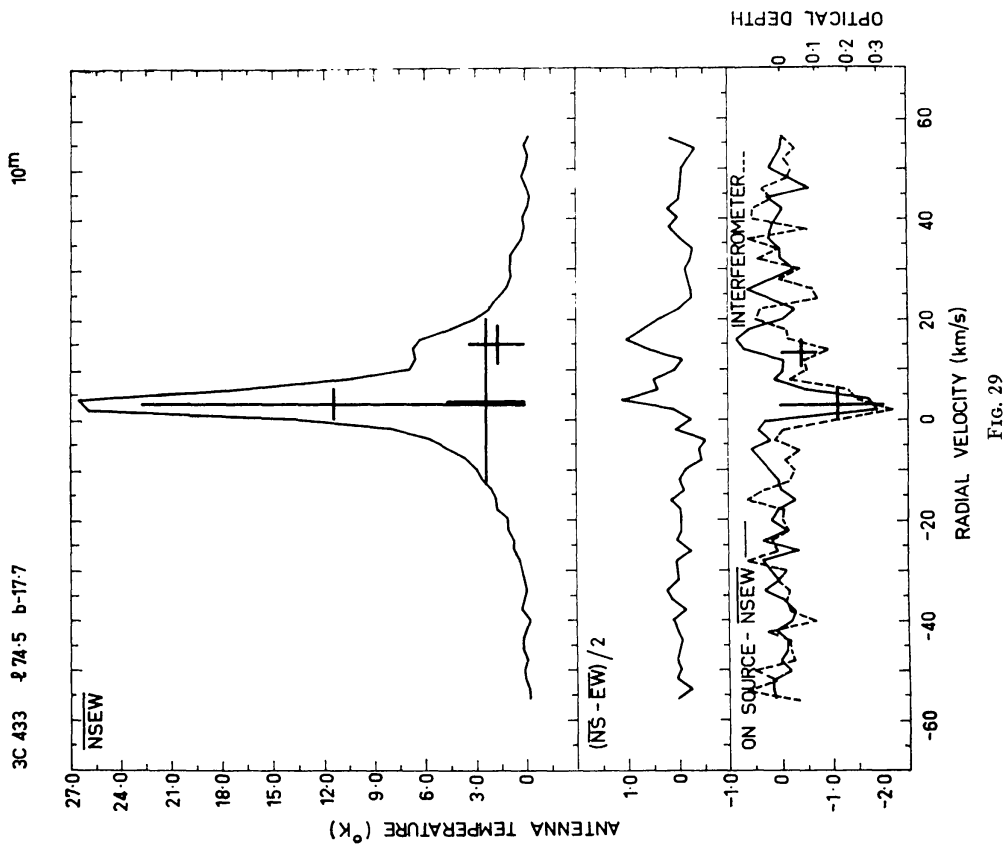


FIG. 28.—2104—25.

FIG. 29.—3C 433.

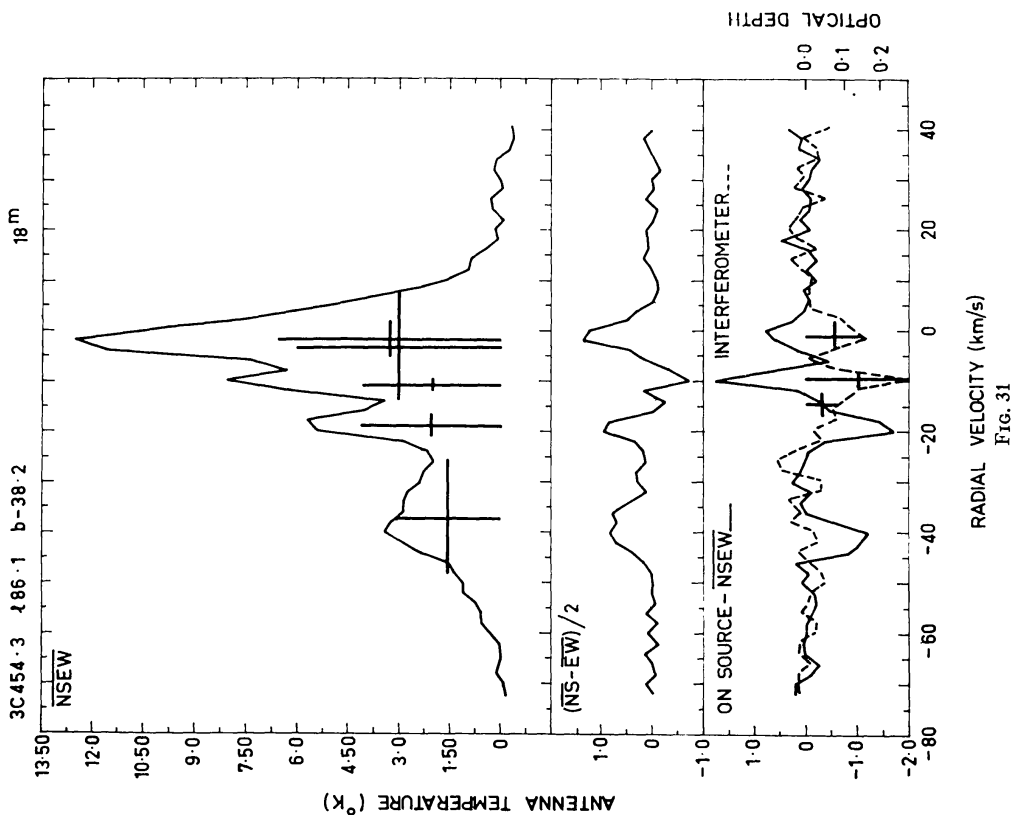
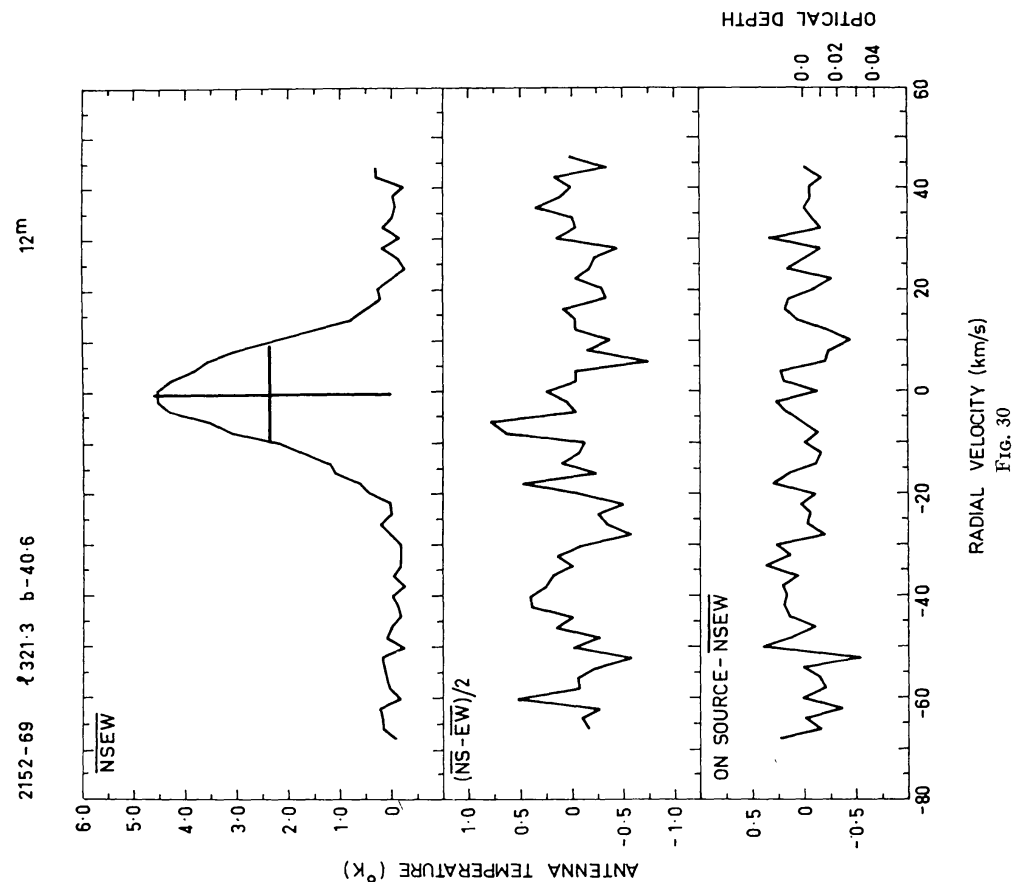


FIG. 30.—2152-69.
FIG. 31.—3C 454.3.



EXPLANATORY NOTES TO FIGURES 4-31

21-cm emission and absorption profiles in the directions of 28 extragalactic sources. All profiles were obtained with filters of width 10 kHz spaced 9.5 kHz (2.0 km s^{-1}), except for those shown in Figures 19b, 21b, and 23b. These were obtained with 1-kHz filters spaced by their own width. All radial velocities are with respect to the local standard of rest. The upper part of each figure shows the emission profile obtained by averaging regions one beamwidth away and is labeled NSEW. The lower part of each figure shows the difference between the profile obtained on source and that shown in the upper part of the figure. Where an interferometer measurement of the absorption is shown superposed, the scales of optical depth indicated on the right have been made to agree. The middle part of each figure shows half the difference between the north-south and east-west averages and is intended to provide some indication of the non-linear gradients in the emission. Crosses indicate Gaussian components fitted by computer program to the brightness temperatures of emission profiles or to the optical depths of absorption profiles.

Equal amounts of time were generally spent in integrating on and off the source position. The integration time for any of these measurements is shown in minutes at the top right-hand corner of a figure. If an interferometer measurement on the source involved a significantly greater length of time, this is indicated in the figure to the right of the absorption profile. In one particular case, the stronger component of the double source For A (Fig. 5), emission profiles were obtained only north and south of the continuum source. The north profile and the north-south average are shown in the upper part of Figure 5. There is naturally no $(NS - EW)/2$ plot for this source as there is in the middle part of all the other figures.

Unambiguous detection of absorption was achieved in the spectra of only about half of the 35 sources observed with the single dish. On the other hand, 13 out of 14 interferometer observations clearly revealed measurable optical depths. The signal-to-noise ratio achievable in a given time with the 64-m dish alone was considerably higher than that obtained with the interferometer arrangement. However, the errors introduced by emission variations more than offset this advantage. Examples of the errors and distortions present in the single-dish absorption profiles can be seen by comparing the two types of spectra obtained on all but those sources with absorption antenna temperatures comparable to the emission antenna temperatures. An instance of striking disagreement is seen in Figure 15, where absorption profiles of both types obtained on the source Hya A are shown. The single-dish profile shows an apparent absorption feature clearly not present in the interferometer spectrum. This is a particularly bad case, as no indication of emission variations is provided in the $(NS - EW)/2$ profiles. It appears that the nonlinear gradients have some form of symmetry about the source position. This would be the case, for example, if there were a depression in the brightness temperature centered very close to the source.

V. ANALYSIS

Thirty-seven features in the absorption spectra of 20 of the sources observed are listed in Table 2. Thirty-four of these features were fitted with Gaussians by a computer program which first converted the observed deflections to optical depths. The remaining three features were estimated by eye, and are listed in the table without any errors attached. In fitting Gaussians to the absorption spectra, no account whatever was taken of the associated emission profiles. The number of components specified was always the minimum required for a satisfactory fit to within the experimental errors. The components of the fit are indicated in the figures by crosses showing the peak optical depth and the full width at half-optical depth. In Table 2, the type of measurement (single-dish or interferometer) is indicated in column (3), and in the next three columns the radial velocity, peak optical depth, and full width at half optical depth of the component are given, together with their associated errors. The last column lists a quantity obtained by integrating under the component and is equal to the column density of hydrogen divided by the spin temperature. For the purpose of this analysis we have in almost all cases used the interferometer observation where both types were

TABLE 2
GAUSSIAN FITTING OF ABSORPTION FEATURES*

Source (1)	Filter Separation (kHz) (2)	Type of Measure- ment (3)	Radial Velocity (km s ⁻¹) (4)	$\tau_{\max}$ (5)	$\Delta V_{1/2}$ (km s ⁻¹) (6)	$N_{\text{H}}/T_{\text{s}}^{\dagger}$ (cm ⁻² ° K ⁻¹) (7)
3C 98.....	9.5	I	9.9 ± 0.3	0.9 ± 0.2	3.7 ± 0.6	6.3 × 10 ¹⁸ (15)
0410-75...	9.5	I	~2.0	~0.2	...	...
3C 138.....	9.5	I	0.62 ± 0.2	0.32 ± 0.05	7.5 ± 0.5	4.7 × 10 ¹⁸ (15)
			6.8 ± 0.2	1.3 ± 0.2	3.3 ± 0.5	8.0 × 10 ¹⁸ (10)
0531+19...	9.5	I	5.1 ± 1.5	0.4 ± 0.2	8.0 ± 3	5.9 × 10 ¹⁸ (35)
30 Dor.....	9.5	SD	5.1 ± 0.4	0.04 ± 0.006	7.9 ± 0.5	5.8 × 10 ¹⁷ (20)
			9.1 ± 0.4	0.1 ± 0.03	2.9 ± 0.5	5.5 × 10 ¹⁷ (15)
3C 161.....	9.5	I	4.9 ± 2.1	0.13 ± 0.07	10.7 ± 4.3	2.8 × 10 ¹⁸ (35)
			6.7 ± 0.2	1.08 ± 0.13	3.3 ± 0.3	6.9 × 10 ¹⁸ (6)
			12.6 ± 0.2	0.70 ± 0.05	5.1 ± 0.3	7.0 × 10 ¹⁸ (5)
			20.0 ± 0.2	0.34 ± 0.03	5.3 ± 0.3	3.6 × 10 ¹⁸ (9)
			28.0 ± 0.2	0.16 ± 0.04	3.9 ± 0.3	1.2 × 10 ¹⁸ (22)
			36.0 ± 0.2	0.15 ± 0.03	3.9 ± 0.3	1.2 × 10 ¹⁸ (20)
0634-20...	9.5	SD	~15.0	~1.0	...	...
3C 273.....	9.5	SD	6.7 ± 1.0	0.03 ± 0.03	...	...
M87.....	9.5	SD	7.3 ± 1.4	0.008 ± 0.004	9.2 ± 2.8	1.5 × 10 ¹⁷ (25)
Cen A.....	9.5	SD	6.1 ± 0.1	0.15 ± 0.008	6.0 ± 0.24	1.8 × 10 ¹⁸ (4)
Cen A.....	9.5	I	6.0 ± 0.6	0.13 ± 0.03	6.3 ± 1.2	1.6 × 10 ¹⁸ (16)
Cen A.....	1.0	SD	6.7 ± 0.2	0.16 ± 0.01	5.7 ± 0.3	1.8 × 10 ¹⁸ (5)
3C 327.....	9.5	I	1.8 ± 1.3	0.19 ± 0.17	4.1 ± 2.8	1.5 × 10 ¹⁸ (55)
16-61.....	9.5	I	0.6 ± 1.0	0.22 ± 0.10	7.0 ± 2.3	3.0 × 10 ¹⁸ (25)
			4.8 ± 0.3	0.65 ± 0.14	2.4 ± 0.4	3.0 × 10 ¹⁸ (15)
16-61.....	1.0	SD	0.4 ± 0.2	0.25 ± 0.03	4.2 ± 0.4	2.0 × 10 ¹⁸ (8)
			4.4 ± 0.1	0.48 ± 0.03	2.4 ± 0.2	2.2 × 10 ¹⁸ (4)
Her A.....	9.5	I	3.5 ± 0.2	0.10 ± 0.01	6.0 ± 0.25	1.1 × 10 ¹⁸ (14)
			0.2 ± 0.2	0.50 ± 0.06	3.2 ± 0.3	3.1 × 10 ¹⁸ (10)
			7.0 ± 0.2	0.10 ± 0.04	2.6 ± 0.3	5.1 × 10 ¹⁷ (30)
3C 353.....	9.5	I	0.2 ± 0.1	1.12 ± 0.08	3.0 ± 0.15	6.6 × 10 ¹⁸ (5)
			2.5 ± 0.1	0.86 ± 0.06	2.6 ± 0.12	4.4 × 10 ¹⁸ (5)
3C 353.....	1.0	SD	0.16 ± 0.06	1.01 ± 0.06	2.8 ± 0.13	5.4 × 10 ¹⁸ (4)
			2.60 ± 0.05	0.90 ± 0.05	2.2 ± 0.1	3.8 × 10 ¹⁸ (4)
1733-56...	9.5	SD	3.7 ± 0.6	0.62 ± 0.16	5.8 ± 1.1	7.0 × 10 ¹⁸ (20)
1814-63...	9.5	SD	2.3 ± 0.7	0.18 ± 0.05	7.7 ± 1.7	2.7 × 10 ¹⁸ (20)
3C 409.....	9.5	I	4.1 ± 0.4	0.5 ± 0.1	4.1 ± 0.8	3.9 × 10 ¹⁸ (15)
			8.5 ± 0.1	0.3 ± 0.03	5.3 ± 0.25	3.1 × 10 ¹⁸ (10)
			14.8 ± 0.2	1.4 ± 0.1	3.9 ± 0.3	10.5 × 10 ¹⁸ (6)
			23.0 ± 0.1	0.1 ± 0.04	4.4 ± 0.3	1.0 × 10 ¹⁸ (40)
2104-25...	9.5	SD	~2.0	~0.1	...	...
3C 433.....	9.5	I	2.9 ± 0.7	0.34 ± 0.13	6.0 ± 1.7	3.9 × 10 ¹⁸ (26)
			13.8 ± 0.7	0.1 ± 0.06	5.9 ± 1.6	1.1 × 10 ¹⁸ (60)
3C 454.3...	9.5	I	-14.5 ± 0.4	0.09 ± 0.03	4.7 ± 0.6	0.8 × 10 ¹⁸ (30)
			-10.2 ± 0.4	0.29 ± 0.1	3.0 ± 0.7	1.7 × 10 ¹⁸ (24)
			-1.6 ± 0.4	0.15 ± 0.04	5.3 ± 0.7	1.6 × 10 ¹⁸ (20)

* Errors quoted (2 × rms value) reflect the quality of the Gaussian fit only. For single-dish measurements, a good fit does not establish the reality of absorption.
† Figures in parentheses are percentage errors.

available. For two or three strong sources with single-dish observations of higher sensitivity than the interferometer ones, we have analyzed both types and listed them in Table 2. No correction for instrumental broadening has been applied to the absorption linewidths listed in column (6) of Table 2 or to any other linewidths listed in subsequent tables.

If absorption features are manifestations of density concentrations along the line of sight, it is very reasonable to look for counterparts to these features in the associated

emission spectra. As discussed earlier, under the conditions of the observations reported here one would expect the emission profile to be an exact scaled reflection of the absorption profile if all the hydrogen were at the same temperature. When the two spectra are compared, one is immediately struck by a consistent dissimilarity, and the degree of dissimilarity depends only on the signal-to-noise ratio of the absorption measurement. When the emission profiles are resolved into Gaussian components, there is always a low, wide component which is absent in the absorption spectra. This phenomenon is unmistakably demonstrated in Figure 32, where we compare pairs of spectra on eight sources selected on the basis of high signal-to-noise. Precisely the same behavior can be seen less clearly in the spectra of 11 out of the remaining 12 sources in Table 2.

The resolution of brightness-temperature profiles into Gaussian components, although widely practiced, is justifiable only for low optical depths. In the case of the emission profiles in this paper the associated absorption measurements indicate the optical depths at the various velocities and provide a guide as to the reliability with which Gaussian fitting may be attempted on them. The worst cases are not the most complicated emission profiles but are rather the ones associated with complicated absorption spectra with nonnegligible optical depths. Excluding a few sources like 3C 161 and 3C 409, we have computer-resolved the emission profiles for most of the sources listed in Table 2. The analysis almost invariably yielded a low, wide component such as seen in Figure 32 and one or more narrower components which corresponded with absorption features. These components are shown in the various figures by crosses similar to those used for the absorption features. We have also fitted Gaussian functions to the emission profiles for a few sources not listed in Table 2 and for which the maximum optical depths were less than 0.05. The results of this analysis on the emission profiles are presented in Tables 3 and 4, where we list respectively the optically "thin" components and those with measurable opacities.

TABLE 3
THE OPTICALLY THIN COMPONENT

Source (1)	Radial Velocity (km s ⁻¹) (2)	Peak <i>T_B</i> (° K) (3)	Width $\Delta V_{1/2}$ (km s ⁻¹) (4)	Opacity τ_{max} (5)	Spin Temperature <i>T_s</i> (° K) (6)	Column Density <i>N_{H I}</i> (10 ²⁰ cm ⁻²) (7)	<i>N_{H I} sin b </i> (10 ²⁰ cm ⁻²) (8)
3C 98.....	13.7	4.0	26.6	<0.1	...	2.1	1.1
0410-75...	2.7	8.5	19.6	<0.05	>170	3.2	1.9
3C 138.....	4.4	27.0	19.5	<0.1	>270	10.2	2.0
Pic A.....	9.5	8.4	21.2	<0.02	>420	3.5	2.0
0531+19...	1.7	31.3	23.9	<0.25	...	14.6	1.8
3C 161.....	28.0	~18.0	~50.0	<0.05	>360	12.2	1.7
Hya A.....	3.8	4.4	20.8	<0.05	>325*	1.8	0.8
3C 270.....	-14.0	1.5	29.5	<0.05	...	0.9	0.9
3C 273.....	-13.4	1.3	26.0	<0.02	...	0.6	0.6
M87.....	-14.9	1.3	39.2	<0.002†	>600†	0.8	0.8
Cen A.....	-7.6	7.5	22.3	<0.01	>750	3.2	1.1
3C 327.....	6.6	4.5	26.0	<0.1	...	2.2	1.4
1610-60...	-18.2	13.9	26.5	<0.025	>560	7.2	0.9
Her A.....	1.8	4.7	32.5	<0.03	>160	3.0	1.5
3C 353.....	3.2	10.1	22.0	<0.02	>500	4.4	1.5
1814-63...	-3.2	4.4	33.1	<0.05	...	2.9	1.0
3C 409.....	5.0	~22.0	~28.0	<0.15	...	12.4	1.3
3C 433.....	3.3	5.9	35.0	<0.1	...	4.0	1.2
2152-69...	-0.41	5.7	19.6	<0.05	...	2.2	1.4
3C 454.3...	-5.5	7.5	21.2	<0.05	>150	3.1	1.9

* Minimum harmonic mean temperature calculated using profile peak brightness temperature. The lower limit for the spin temperature of the wide component must therefore be higher than this value.
† Colvin *et al.* (1970).

TABLE 4
GAUSSIAN FITTING OF EMISSION FEATURES CORRESPONDING TO ABSORPTION FEATURES*

Source (1)	Radial Velocity (km s ⁻¹) (2)	Peak <i>T_A</i> (° K) (3)	Width $\Delta V_{1/2}$ (km s ⁻¹) (4)	Peak <i>T_B</i> (° K) (5)	$1 - e^{-\tau}$ (6)†	Spin Temper- ature <i>T_s</i> (° K) (7)	<i>N</i> _{He} Absorption (10 ²⁰ cm ⁻²) (8)†
3C 98.....	9.5±0.1	26.3±2.3	5.0±0.3	33	0.6	56	3.5
0410-75....	3.2±0.2	17.5±1.2	6.9±0.3	22	~0.2	110	...
3C 138.....	1.4±0.1	22.3±0.8	10.1±0.3	28	0.27	103	4.9
	7.6±0.1	29.7±2.0	6.0±0.3	37	0.73	51	4.1
0531+19...	5.7±0.2	44.2±3.0	11.4±0.6	55	0.33	165	9.9
30 Dor.....	- 4.7±0.2	5.8±0.2	12.8±0.4	7	0.04	180	1.1
3C 161†....	4.9	~18	...	23	0.12	190	5
	6.7	~55	...	70	0.66	105	7
	12.6	~52	...	65	0.5	130	9
	20.0	~12	...	15	0.3	50	2
	36.0	~ 8	...	10	0.14	70	0.8
3C 273.....	- 5.6±0.2	4	6.6±0.5	5	0.03	170	0.24
Cen A.....	- 6.1±0.1	24.5±1.5	7.1±0.3	31	0.15	205	3.7
3C 327.....	- 1.7±0.1	19.1±0.8	7.0±0.2	24	0.17	140	2.1
16-61†....	0.4	~31	...	39	0.22	177	3.5
	4.4	~20	...	25	0.38	66	1.4
Her A.....	- 3.6±0.1	2.9±0.5	5.8±0.2	3.6	0.1	36	0.4
	- 0.1±0.1	21.4±1.6	4.8±0.3	27	0.39	69	2.1
	6.6±0.1	10.1±1.0	4.7±0.3	13	0.1	126	0.64
3C 353.....	- 0.3±0.1	29.3±1.3	3.7±0.1	37	0.64	57	3.1
	2.9±0.1	20.4±0.8	4.2±0.1	26	0.59	43	1.6
1733-56...	3.5±0.1	25.2±1.4	5.8±0.2	32	0.46	69	4.8
1814-63...	- 1.9±0.2	16.8±1.0	9.4±0.4	21	0.16	131	3.5
3C 409†....	4.1	~18	...	23	0.4	58	2.2
	8.5	~40	...	50	0.26	190	6.0
	14.8	40±8	...	50±10	0.75	65	7.7
	23.0	~ 6	...	8	0.1	80	0.8
3C 433.....	3.3±0.1	22.8±1.1	6.2±0.2	28.5	0.29	98	3.8
	15.0±0.1	3.4±0.4	7.8±0.2	4.3	0.1	43	0.46
3C 454.3...	-10.8±0.2	4.1±1.1	2.6±0.6	5	0.25	20	0.35
	- 1.9±0.1	6.6±0.4	6.8±0.4	8.3	0.14	59	0.94

* Errors quoted (2 × rms value) reflect the quality of the Gaussian fit only.

† Derived from data for corresponding absorption feature in Table 2.

‡ The antenna temperatures at the absorption velocities were obtained from the emission profile after allowing for the estimated contribution from the optically thin component.

VI. THE OPTICALLY THIN COMPONENT

Twenty sources are listed in Table 3. The emission spectrum in the direction of each of these contains an optically thin component whose mean radial velocity, peak brightness temperature, and full width at half-intensity are listed in columns (2), (3), and (4), respectively. Except in the case of two sources all the parameters listed in these columns were obtained by computer-fitting. For 3C 161 and 3C 409 (Fig. 32) the low, wide component was estimated by interpolation between the limiting velocities of the absorption spectra and taking into account the shapes of the emission profiles. Fourteen of the sources show definite absorption over part of the velocity range of their associated emission spectra. Of the remaining six sources, four show no trace of absorption and two (3C 273 and M87) show only very weak features in our measurements. Colvin *et al.* (1970) have observed M87 with an interferometer and have obtained roughly twice

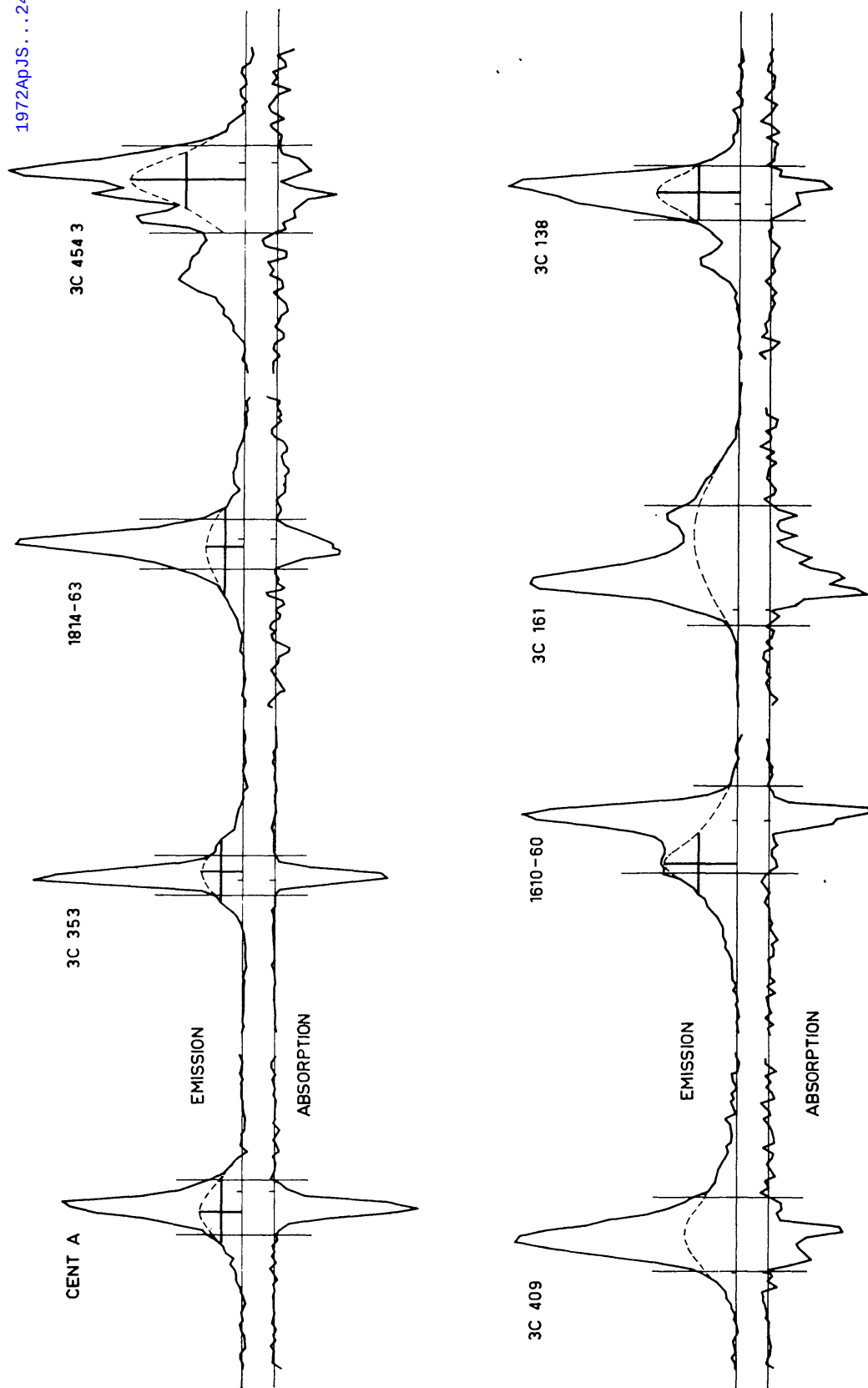


FIG. 32.—Comparison of eight emission and absorption spectra obtained at intermediate latitudes and selected on the basis of high signal-to-noise ratio. The velocity limits of the absorption spectra are demarcated, showing clearly the presence of an optically thin component in every emission spectrum. These components are shown by dashed lines. In six cases (*crosses*) the parameters of the low, wide component were determined by a computer analysis into Gaussians. See text for discussion.

the optical depth indicated by our single-dish measurement. They find that the absorption is concentrated over the velocity range of the peak in the emission profile and that the low, wide component has an optical depth below their limit of measurement.

In column (5) we have listed upper limits to the optical depths associated with those components of the emission profiles whose parameters are listed in columns (2)–(4). In estimating these limits we have generally used the more reliable interferometer measurements where both types were available. In the case of Cen A, 3C 353, and 1610–60, we have used single-dish measurements because of their greater sensitivity. The justification is in the excellent agreement found between the two types of measurement for these three sources. For this reason they were also observed with the single-dish, using 1-kHz filter widths, and the detailed shapes of the absorption spectra were determined to considerable accuracy. By combining the upper limits to the optical depths with the peak brightness temperatures for these components, we can obtain lower limits to the spin temperature of the hydrogen giving rise to the emission. These lower limits are listed in column (6) for all cases where this limit is in excess of 125° K. It is seen that some of the limits are many times this value and that they are dependent only on the sensitivity of the measurement. In no case, either here or in other investigations, has an optical depth been measured for the wide component present in every galactic emission profile. It would appear that if the wide components of profiles obtained in different directions were related, their spin temperatures might be similar and at least as high as the highest limit obtained so far.

If arguments were necessary to establish the identity of the wide component seen in different profiles, they would be as follows. In no direction can one obtain an emission profile containing only narrow components. In many directions at high latitudes one sees the wide component only (e.g., Pic A, 2152–69). Its width, listed in column (4), ranges from ~ 20 km s $^{-1}$ upward, suggesting that for any reasonable amount of turbulence present the spin temperatures must be very high. (For pure thermal broadening $\Delta V_{1/2} = 20$ km s $^{-1}$ leads to $\sim 10^4$ ° K.) That the spin temperature is higher than any values normally associated with so-called clouds of hydrogen is seen from column (6). The peak brightness temperature shows a definite correlation with galactic latitude in that higher temperatures are associated with lower latitudes, as would be the case for a more or less uniform distribution of optically thin gas.

The column density of this hot hydrogen in the various directions is listed in column (7) of Table 3. In calculating the integrals under the wide components for 3C 138 and 3C 454.3 we have excluded the secondary features at the negative-velocity end. That these features are due to hydrogen concentrations with small-angular-scale structure is seen in Figures 9 and 31, where pseudo-absorption is indicated by the single-dish measurements. The column density listed is seen to vary by a factor of 20 between its extreme values. Any lingering doubt that these numbers, obtained in widely different parts of the sky, refer to separate and isolated concentrations of hydrogen should be dispelled by those listed in the last column of Table 3. Here we have multiplied the column density by $\sin |b|$, thus rendering its value independent of the path length through the galactic disk. The extreme values vary by only a factor of 3, thus suggesting compellingly that the optically thin component of the emission spectra originates in an intercloud medium with only minor variations in density.

Heiles (1967) and Grahl, Hachenberg, and Mebold (1968) found evidence of a diffuse component in the emission at intermediate latitudes. It might be mentioned that the first identification of an extended component of the interstellar hydrogen distribution was by McGee and Murray (1961). From a sky survey of the neutral hydrogen they were led to the conclusion that the local distribution was substantially horizontally stratified and that embedded in it were concentrations of gas. More recently Mebold (1971) has extensively investigated the mean velocity and width of the shallow compo-

nents of emission profiles at a latitude of 30° . He finds a dependence on galactic longitude of just the type expected from differential galactic rotation acting on a more or less uniform distribution of gas. The density of the intercloud medium obtained from his investigations leads to an equivalent column density in excellent agreement with the value obtained here for optically thin gas. The mean column density of this gas along any line of sight as calculated from Table 3 is $1.4 \times 10^{20} \text{ cosec } |b| \text{ atoms cm}^{-2}$. The corresponding density in the plane is $47/h \text{ atoms cm}^{-3}$, where h is half the scale thickness of its z -distribution in parsecs.

VII. THE CLOUD COMPONENT

In Table 4 we list 20 emission components which are obvious counterparts to absorption features listed in Table 2. Their parameters (radial velocity, peak antenna temperature, and full width at half-intensity) are listed in columns (2), (3), and (4) as obtained by computer fitting. In a few cases where the form of the profile or the high optical depths involved would have made computer fitting unreliable, we have obtained antenna temperatures directly from the emission profiles at the appropriate absorption velocities. Column (5) contains the brightness temperatures converted from the antenna temperatures of column (3). The quantity listed in column (6) is from the corresponding absorption component. This quantity may be combined with the brightness temperature to yield the spin temperature in column (7). The spin temperature in turn can be combined with the integral under the absorption component from Table 2 to give the true column density listed in the last column.

A detailed analysis of the available data on interstellar hydrogen concentrations will form the basis of a subsequent publication. It will draw on the information in all the papers in this supplement and also from some special observations now in progress. Here we shall only summarize the immediate conclusions that can be drawn from a cursory analysis of the data in Tables 2 and 4.

The distribution in optical depths of the absorbing clouds is roughly exponential. Their spin temperatures, shown in Table 4, range from 20° to 200° K . The median value for this small sample (30 features) is $\sim 80^\circ \text{ K}$ for all clouds. For the even smaller sample of clouds with $\tau > 0.5$ (10 features) the median value is $\sim 60^\circ \text{ K}$. Most of the features detected in observations close to the plane tend to have $\tau > 0.5$, as seen in the two following papers. The appropriate spin temperature characterizing these dense clouds may be well below 60° K .

If clouds condense out of the intercloud medium, it is only reasonable to expect a range of temperatures for the clouds corresponding to different stages of the final condensation. The observed spread in spin temperatures may well be a manifestation of this process. It is also possible that there is a considerable gradient of spin temperature within a single cloud. Some evidence in support of this idea is found in our measurements. Even after the intercloud component has been removed, there is often a tendency for the emission feature to be wider than the corresponding absorption feature, such as seen in Figures 21*b* and 23*b*. The two emission components in each figure not only are at different spin temperatures but are also considerably wider than their absorption counterparts. Since turbulence alone would have broadened both emission and absorption profiles equally, one is forced to conclude that a colder part in each cloud contributes preferentially to the absorption profile. That considerable turbulence is also present is shown by the widths of the absorption components. These widths are invariably in excess of those expected for thermal broadening at the derived spin temperatures. Verschuur (1969) has found a few very narrow emission lines showing that some clouds at least have spectra not appreciably broadened by turbulence.

The column densities of the absorbing clouds range from 0.25 to $10 \times 10^{20} \text{ atoms cm}^{-2}$ with a mean of 3×10^{20} . If the scale height of the galactic hydrogen is h parsecs

above the plane, then the mean separation along a line of sight between clouds can be shown from Table 4 to be $2h$ parsecs. The mean column density of cloud hydrogen along any line of sight is therefore $1.5 \times 10^{20} \text{ cosec}|b| \text{ atoms cm}^{-2}$.

VIII. BRIGHTNESS OF EMISSION PROFILES

The minimum observed Doppler width of emission from the intercloud medium is $\sim 20 \text{ km s}^{-1}$. For directions where long path lengths can be traversed without the effects of galactic rotation (e.g., $l \approx 0^\circ$ or 180°), the peak brightness temperature of the intercloud radiation is $\approx 4.4 \text{ cosec}|b|$ degrees Kelvin, as obtained from Table 3. In these directions, as the latitude decreases to 5° the path length increases to $\sim 12h$, and the brightness temperature rises to $\sim 50^\circ \text{ K}$, the same order as the brightness temperature of a dense cloud with $\tau \approx 1$. For this path length the line of sight is likely to intersect six clouds of various optical depths. The observed emission profile will be a blend of several contributions, some having the same order of peak brightness as the emission from the medium. Separation of the various contributions is therefore likely to be difficult, if at all possible.

At a latitude of 2° the brightness temperature of the medium alone is now $\approx 125^\circ \text{ K}$. However, there are now likely to be 15 intervening clouds of various optical depths. The observed brightness temperature will therefore be strongly influenced by the line-of-sight distribution of clouds, of which several are likely to be optically thick and cold. At the very low latitudes, the intervening clouds attenuate the enormous contribution to the brightness temperature that would otherwise be obtained from the intercloud medium. As the brightness temperature of the clouds is now lower than that of the medium, absorption of the intercloud radiation by one or more of them in the foreground may stand out. Striking examples of this effect may be seen in the profiles for the sources M8, W28, and several others in Paper III of this Supplement. In all those cases the absorption maxima correspond to sharp decreases in the emission temperatures. At the higher latitudes, as we have seen in the case of every absorption feature in this paper, absorption maxima correspond to emission maxima. The brightness temperature of the clouds is much greater than that of the medium for short path lengths. At other longitudes and low latitudes the effect of galactic rotation will spread out the velocities and complicate the picture (see, for example, Rohlfs 1971).

IX. CONCLUSIONS

The present work has succeeded in its primary objective of identifying the cloud and intercloud components of the interstellar hydrogen distribution by measurements of their opacities. Extragalactic sources situated at intermediate latitudes appear to be most suited for this type of investigation, and the interferometer seems the best instrument for observing them. The clouds have column densities ranging from 0.25 to 10 times $10^{20} \text{ atoms cm}^{-2}$ with a mean of 3×10^{20} , and their spin temperatures range from 20° to 200° K with a mean of 80° K . The distribution of the cloud component is such that any line of sight intersects about one cloud per full scale-thickness of the galaxy. The diffuse intercloud medium has an opacity below the limit of measurement, providing only lower limits for the spin temperature. The highest such limit is 750° K . The column density of the medium in the solar neighborhood can be expressed as $1.4 \times 10^{20} \text{ cosec}|b| \text{ atoms cm}^{-2}$. The corresponding average value for the cloud hydrogen is $1.5 \times 10^{20} \text{ cosec}|b| \text{ atoms cm}^{-2}$. The neutral gas is therefore equally divided between clouds and the intercloud medium to within the errors of measurement.

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REFERENCES

- Batchelor, R. A., Brooks, J. W., and Sinclair, M. W. 1969, *Proc. IREE, Australia*, **30**, 39.
- Clark, B. G. C. 1965, *Ap. J.*, **142**, 1398.
- Colvin, R. S., Hughes, M. P., Thompson, A. R., and Verschuur, G. L. 1970, *Ap. Letters*, **6**, 211.
- Field, G. B., Goldsmith, D. W., and Habing, H. J. 1969, *Ap. J. (Letters)*, **155**, L149.
- Goss, W. M., Radhakrishnan, V., Brooks, J. W., and Murray, J. D. 1971, *Ap. J. Suppl.*, No. 203 (Paper IV).
- Grahl, B. H., Hachenberg, O., and Mebold, U. 1968, *Beiträge z. Radioastr.*, **1**, 1.
- Heiles, C. 1967, *Ap. J. Suppl.*, **15**, 97.
- Hughes, M. P., Thompson, A. R., and Colvin, R. S. 1971, *Ap. J. Suppl.* (in press).
- McGee, R. X., and Murray, J. D. 1961, *Australian J. Phys.*, **14**, 260.
- Mebold, U. 1969, *Beiträge z. Radioastr.*, **1**, 97.
- . 1971, preprint.
- Radhakrishnan, V., Brooks, J. W., Goss, W. M., Murray, J. D., and Schwarz, U. 1971a, *Ap. J. Suppl.*, No. 203 (Paper I).
- Radhakrishnan, V., Goss, W. M., Murray, J. D., and Brooks, J. W. 1971b, *Ap. J. Suppl.*, No. 203 (Paper III).
- Radhakrishnan, V., and Murray, J. D. 1969, *Proc. Astr. Soc. Australia*, **1**, 215.
- Rohlf, K. 1971, *Astr. and Ap.* (in press).
- Troitzky, V. S., and Krotikov, V. D. 1968, *Radiophys. USSR*, **11**, 1135.
- Van Woerden, H. 1967, Report of informal discussion on coordination of brightness temperature scales used in 21-cm line studies held at I.A.U., Hamburg, 1964.
- Verschuur, G. L. 1969, *Ap. Letters*, **4**, 85.
- Williams, D. R. W. 1965, *Quasi-stellar Sources and Gravitational Collapse*, ed. I. Robinson, A. Schild, and E. L. Schucking (Chicago, University of Chicago Press), p. 213.
- . 1970, paper presented at I.A.U. meeting, 1970.