PAPER 13

21-CM. ABSORPTION EFFECTS

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In the discussion which follows, there are presented three areas of the Naval Research Laboratory's study of absorption effects in the spectra of discrete sources produced by interstellar hydrogen. The first topic presented is the theory of the two mechanisms which are operative in producing the observed absorption effects. The second area of the discussion presents the observations and their interpretations for sources which lie in directions where the effects of galactic rotation are an important aid in the interpretation of the observed absorption. When galactic rotation effects are small, special techniques must be developed to supplement the absorption effect in order to determine distances to the discrete source. An example of the latter technique is contained in the third topic presented here, in a study of the source Sagittarius A. All the data discussed here were obtained with the Naval Research Laboratory's 21-cm. radiometer in conjunction with the 50-ft. antenna. A signal band width of 5 kc. (1 km./sec.) was employed throughout.

1. THEORY OF THE ABSORPTION EFFECT

We closely follow here the discussion first presented by Lilley at the Princeton Meeting of the American Astronomical Society, 1955 [1]. The basic problem of interpretation of the observational data is contained in Fig. 2, Cassiopeia A, which shows that the 21-cm. profile for the exact direction of a discrete source is radically different compared to any adjacent profile. We are immediately led to suppose that, in the absence of the discrete source, the 21-cm. profile for the source direction would be equivalent to the profiles which characterize the adjacent part of the sky. We shall call this profile the 'expected profile' and the profile actually obtained in the direction of the discrete source the 'observed profile'.

If the radio source lies in the centre of the antenna reception beam, the observed absorption of the discrete source radiation by interstellar H I is effective only over the small solid angle, Ω_S, subtended by the discrete source. However, all the H I gas in the antenna beam of larger solid angle Ω_B contributes to the H I emission. Thus the difference between the expected and observed profiles is due only to that gas lying within the solid angle subtended by the discrete source.

Consider a discrete source embedded in the interstellar medium and viewed by an antenna (Fig. 1). Three spatial volumes are obvious in the figure. The projection of the configuration is shown schematically at the right. Call $\Delta T_1(\nu)$, $\Delta T_2(\nu)$ and $\Delta T_3(\nu)$ the 21-cm. profiles which would result from observations of these regions individually in the absence of the others, and in the absence of the source. Zones 1 and 2 have H I opacities given by $\tau_1(\nu)$ and $\tau_2(\nu)$. The apparent antenna temperature of the discrete source is T_A, and its continuous opacity is given by τ_S.

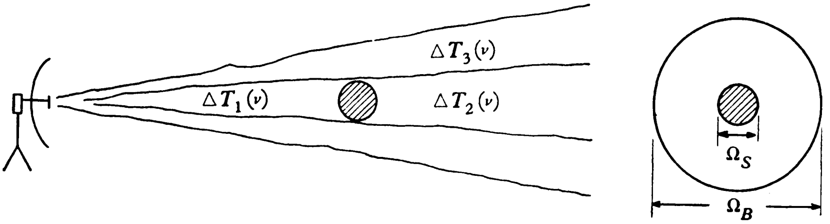

Fig. 1. Schematic representation of the three zones of H I which may be considered separately in the development of the absorption effect. Zones 1, 2, and 3, are those in which $\Delta T_1(\nu)$, $\Delta T_2(\nu)$, and $\Delta T_3(\nu)$ are found in the diagram. The projected configuration, showing the discrete source in the antenna beam, is shown at the right.

Then the expected profile is given by

$$\overline{\Delta T}(\nu) = \Delta T_1(\nu) + \Delta T_2(\nu)\, e^{-\tau_1(\nu)} + \Delta T_3(\nu) \tag{1}$$

and the observed profile by

$$\Delta T'(\nu) = \Delta T_1(\nu) + \Delta T_2(\nu)\, e^{-\tau_S}\, e^{-\tau_1(\nu)} + \Delta T_3(\nu) + T_A e^{-\tau_1(\nu)} - T_A, \tag{2}$$

where the last T_A in (2) is subtracted instrumentally.

Since we may write $\Delta T_2(\nu)$ as

$$T_K\,(1 - e^{-\tau_2(\nu)})\,\frac{\Omega_S}{\Omega_B}$$

the difference between the expected and observed profiles then becomes

$$\overline{\Delta T}(\nu) - \Delta T'(\nu) = T_A(1 - e^{-\tau_1(\nu)}) + T_K(1 - e^{-\tau_2(\nu)})\,(1 - e^{-\tau_S})\,e^{-\tau_1(\nu)}\,\frac{\Omega_S}{\Omega_B}. \tag{3}$$

Note that if the source is extra-galactic ($\tau_2(\nu) = 0$) or if the continuous opacity of the source is small ($e^{-\tau_S} \sim 1$) or if the angular size of the source is small, $\frac{\Omega_S}{\Omega_B} \ll 1$, then the last term in (3) may be neglected. One may then solve for the opacity $\tau_1(\nu)$ with the aid of observational and derived data as,

$$\tau_1(\nu) \simeq -\ln\left(1-\frac{\overline{\Delta T}(\nu)-\Delta T'(\nu)}{T_A}\right). \tag{4}$$

2. OBSERVATIONAL RESULTS FOR CASSIOPEIA A, CYGNUS A AND TAURUS A

The most striking case of the effect is the results obtained for the Cassiopeia source (Hagen, Lilley and McClain, 1955) [2]. The basic data are shown in Fig. 2. In Fig. 2, the profile for the comparison position is characteristic of the Cassiopeia region and is very nearly equivalent to the 'expected profile' which is obtained through a careful average of adjacent profiles at galactic latitudes identical with Cassiopeia A. The features for the profile obtained when the source was in the beam clearly show the effect of the H I gas within the small solid angle subtended by the radio source. The absorption features are interpreted as the effect of separate interstellar H I condensations which lie within the solid angle Ω_S. The distances of the H I clouds must be evaluated before a minimum distance to the radio source

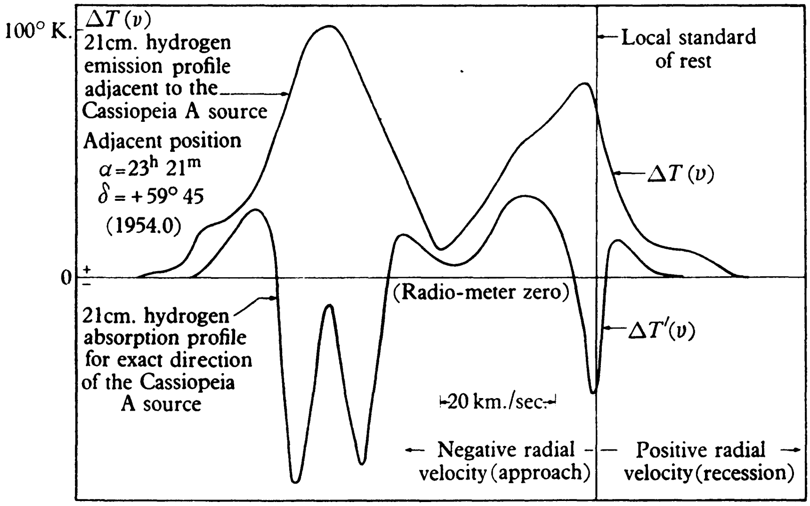

Fig. 2. Profile-type absorption measurement. Two 21-cm. hydrogen-line profiles are shown, one for the direction of the Cassiopeia A source and one for a comparison position approximately one degree away.

may be determined. A simple galactic rotation analysis places one cloud in the immediate vicinity of the sun, the local arm, and two in the second spiral arm, the Perseus arm, at a distance of about 3 kiloparsecs. On this basis, the minimum distance to the radio source is 3 kiloparsecs.

There remains the doubtful possibility that the three H I clouds are all actually nearby, and simply have radial velocities which are of the proper magnitude to fall in the radial velocity range of the second arm.

Absorption studies have been made in a similar fashion for Taurus A and Cygnus A. The Cygnus source is several degrees out of the galactic plane and the expected profile shows a strong emission from the near arm but a weaker intensity from the far arm. An easily detectable absorption exists in the near arm, but any effect in the far arm is too small for the 50-ft. antenna and present radiometer to detect. The measurements then place the source beyond the first arm and do not deny the possibility that the source is an extra-galactic object.

There is a clear case of absorption for the Taurus A radio source, which is located in the anti-centre region where galactic rotation analysis is almost impossible. The absorbing hydrogen cannot therefore be easily placed in terms of galactic distances. The profile for Taurus A is very nearly centred on the local standard of rest. The absorption effect covers the peak of the profile and extends to the positive radial velocity wing. The negative wing of the profile exhibits no absorption, indicating that the gas responsible for the negative wing of the profile lies beyond the radio source.

3. THE SPECIAL CASE OF SAGITTARIUS A

Figs. 3 and 4 summarize the work to date of McClain (1955) [3] in the direction of the galactic centre. Fig. 3 shows the expected profile $\Delta \overline{T}(\nu)$, the observed profile $\Delta T'(\nu)$ and the derived optical depth $\tau_1(\nu)$, at the position $l = 327^\circ.8$ and $b = -1^\circ.4$. It is seen that gas in the wings of the profile is not effective in absorbing continuum radiation from the radio source and hence may be interpreted as being beyond the source. This figure does not yield information about the absolute distance of various features in the profile. An alternative explanation that the non-absorbing gas is in the edge of the antenna beam is unlikely for two reasons. First, studies of the angular distribution of gas in the wings indicate that while the gas is of limited angular extent, the angular size is well in excess of the beam-width and is centred very close to the source. Secondly, if only a portion of the beam were filled with a small gas cloud the emission intensity would suffer by the ratio of the solid angle of the beam to the solid angle of the gas cloud. The emission temperature of the observed profile in the range -15 km./sec. to -20 km./sec. where absorption is known to be absent is of the order of 50° K. This temperature is characteristic of the region at this velocity and would seem to preclude a partially filled beam.

An independent distance scale has been obtained by assuming a constant thickness for the hydrogen gas and by relating the angular extent of the gas to its radial velocity.

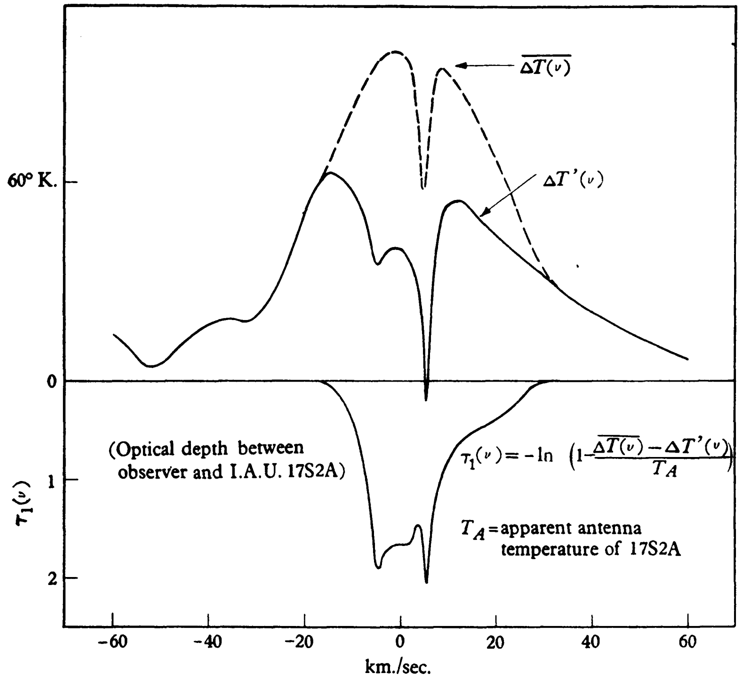

Fig. 3. The expected profile $\overline{\Delta T}(\nu)$ and the observed profile $\Delta T'(\nu)$ for the direction of 17S2A are shown at the top. The computed value of the optical depth is shown at the bottom on a common velocity scale.

If one assumes that the Galaxy is a flat disk of thickness t an observer inside the disk can relate the angular width ϕ of the disk to the distance d at which the angle was measured by the relation

$$\tan\frac{\phi}{2} = \frac{t}{2d}.$$

The assumption that the Galaxy is of uniform thickness is obviously not rigorous but a more complicated model would hardly be justified. The angular extent of the gas was measured by two different methods. First, a number of profiles were taken at positions along a line normal to the plane at $l=327^{\circ}.8$ (Lund pole). The positions were symmetrically spaced about $b=-1^{\circ}.4$. The central position $l=327^{\circ}.8$ and $b=-1^{\circ}.4$ is the measured position of 17S2A at 21 cm. Profiles were taken at $\pm 0^{\circ}.5$, $\pm 1^{\circ}.0$, $\pm 1^{\circ}.5$, $\pm 2^{\circ}.5$ and $\pm 4^{\circ}$ with respect to $b=-1^{\circ}.4$. Temperatures at corresponding radial velocities on the profiles were then plotted as a function of angle. Profiles taken in this manner do not yield a satisfactory measure of angular extent at velocities lower than ± 10 km./sec. This is a result of the large Ophiuchus dark complex (Heeschen and Lilley, 1954) [4] which makes an angle of about 20° with the galactic plane. For this reason

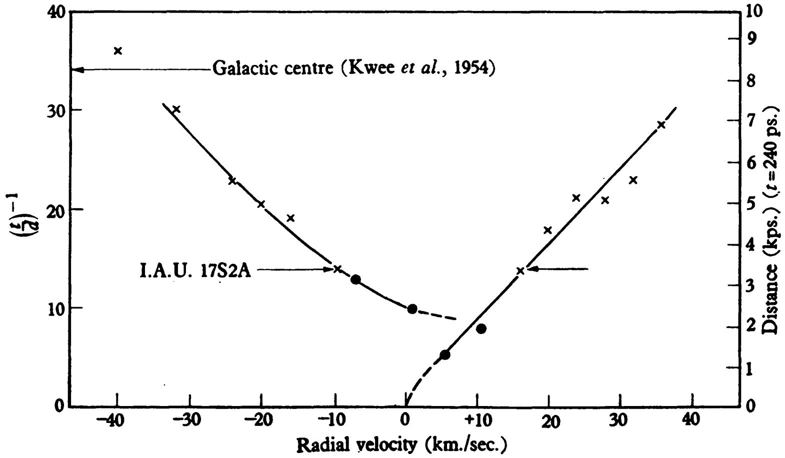

Fig. 4. Diagram showing the relation between distance and radial velocity obtained from the measurements reported herein. The left-hand ordinate is the dimensionless quantity $(t/d)^{-1}$. This quantity is the cotangent of the full half-intensity width. The right-hand ordinate is a distance scale derived by assuming a uniform thickness of 240 parsecs for the Galaxy.

declination sweeps (which avoid the complex) corrected to equivalent widths normal to the plane were used as the measure of angular extent at the lower radial velocities. The angular extent of the gas was taken as the measured one-half intensity point.

The data obtained in these measurements are illustrated in Fig. 4. The left-hand ordinate is the dimensionless quantity $\left(\frac{t}{d}\right)^{-1}$ (cotangent of the full one-half intensity width). The right-hand ordinate is the distance scale obtained by assuming a thickness of 240 parsecs. The abscissa is the radial velocity with respect to the local standard of rest. The crosses are the values taken from the hydrogen profiles and the dots are those obtained by means of angular sweeps. Both the positive and negative wings are seen to reach values commensurate with the value of $1^{\circ}.7$ at 8·2 kiloparsecs given by

Kwee, Muller, and Westerhout (1954) [5] for the galactic centre. Of primary interest, however, is the region within 4 kiloparsecs of the sun. It will be noted that there is an indication of a double-valued distance at about +5 km./sec. This is a necessary condition if one invokes the self-absorption hypothesis of Heeschen (1955) [6]. An attempt at a direct measurement of the angular extent of the more distant gas at +5 km./sec. leads to ambiguities and its existence can only be inferred by the notch in the profiles surrounding the centre.

Up to this point no account has been taken of differential galactic rotation. The effect of differential rotation when an antenna beam of finite size is pointed at the centre will be to increase the apparent velocity dispersion of the observed profile. Quantitative checks of this effect using the Dutch rotational velocities reveal that the observed dispersion at intermediate distances is several times that expected from pure rotation. For example, at a distance of 5 kiloparsecs from the sun the dispersion expected from a one degree beam would be about 2 km./sec. Fig. 4 reveals, however, that the observed velocities present at 5 kiloparsecs are of the order of 25 km./sec. Therefore, a consideration of the Dutch rotational velocities in conjunction with the measurements reported here leads to the conclusion that the random velocity η probably increases rather rapidly beyond 2 kiloparsecs from the sun, and Fig. 4 may be considered a measure of this dispersion.

In applying the distance scale to radio source 17S2A one is forced to consider the random motions present at the distance of the source. These random motions have the effect of making it difficult to associate a particular value of radial velocity with the onset of absorption. In Fig. 3 it is seen that $\tau_1(\nu)$, and hence absorption, occurs from −16 km./sec. to +32 km./sec. If one assumes that the correct value of $\tau_1(\nu)$ lies between 0·1 and 0·5 of the maximum value, the limits placed on the associated radial velocities are −7 km./sec. to −12 km./sec. for the negative wing and +10 km./sec. to +24 km./sec. for the positive wing. These velocities place the distance of the source between 3 and 4 kiloparsecs for the negative branch of Fig. 6 and between 2 and 5 kiloparsecs for the positive branch. Since the positive and negative branches have different slopes it is of interest to determine at what value of $\tau_1(\nu)$ and hence at what velocity the positive and negative branches yield the same distance. The value of $\tau_1(\nu)$ at which this occurs is 0·5 (25 % of the maximum value) and the distance indicated by both branches of the distance scale is 3·4 kiloparsecs. This value is indicated by arrows in Fig. 4.

A consideration of the measurements reported herein leads to the conclusion that the radio source responsible for the intense emission peak at $l = 327\overset{\circ}{.}8$ and $b = -1\overset{\circ}{.}4$ is probably not associated with the galactic centre but rather is superimposed on the broad central galactic background. A consideration of the uncertainties of the measurement places it between extreme limits of 2 and 6 kiloparsecs with a probable distance between 3 and 4 kiloparsecs. It is interesting to note that Haddock and McCullough (1955) [7] have suggested that this source is thermal and possibly associated with an H II region in the group of OB stars studied by Hiltner (1954) [8]. The mean distance given by Hiltner for this group is 3 kiloparsecs. It should be noted that the apparent position of a complex source might vary with the wave-length at which the observation is made and with the antenna beam size if the sources are not exactly concentric. Such variation has been noted for this source.

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Discussion

Lilley: We have a distance discrepancy to Cassiopeia A of approximately a factor of six between the radio analysis of the absorption profile and the optical determination which has just been mentioned by Minkowski. The radio distance depends directly on the assumption that the absorption features at −38 and −48 km./sec. are produced by H I gas located in the second spiral arm. If the smaller optical distance is correct we must differently interpret the radio absorption profile and account for the negative velocity features. The possibility of nearby interstellar clouds has been mentioned. A second possibility also exists—the cool absorbing gas may be dynamically associated with the radio source itself. This situation could conceivably satisfy the velocity and geometrical projection requirements of the absorbing H I gas.

Greenstein: The conclusion that there is an interaction between the Cas source and the recoiling H I clouds in the vicinity can hardly be avoided. Could the Cas source have a cold H I envelope? The sharpness of the absorption components in the Cas A source is very unusual and striking.