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POSITIVE DETERMINATION OF AN INTERSTELLAR MAGNETIC FIELD BY MEASUREMENT OF THE ZEEMAN SPLITTING OF THE 21-cm HYDROGEN LINE

G. L. Verschuur
National Radio Astronomy Observatory,* Green Bank, West Virginia
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Fields of the order of 2×10^{-5} G exist in the Perseus spiral arm in the direction of the radio source Cassiopeia A.

A new attempt to determine the interstellar magnetic field strength by measurement of the Zeeman splitting of 21-cm neutral hydrogen spectra has been successful. The results indicate that fields of 20×10^{-6} G (20 μG) exist in the Perseus spiral arm in the direction of Cassiopeia A, whereas no fields of this order have been found in four local spectral features.

The experiment was done at the National Radio Astronomy Observatory, using the new 416-channel digital spectrometer in conjunction with the 140-ft telescope. The dish was illuminated by a pair of crossed dipoles mounted in a shallow circular waveguide so as to produce circular beam patterns. The dipoles fed a hybrid directly, and the digital correlator alternately sampled the left- and right-hand polarized outputs by means of a reed switch operating at 1 Hz. The 416-channel autocorrelator was operated as two separate spectrometers of 192 channels, each with different overall bandwidths. Those used were 156, 312, and 625 kHz, giving an effective resolution of 0.98, 1.97, and 3.94 kHz/channel, respectively.

Four regions were examined for Zeeman splitting effects. These were the absorption spectra of Cas A ($l^{\rm II}=111.5°$, $b^{\rm II}=0.2°$) and Tau A ($l^{\rm II}=184.5°$, $b^{\rm II}=-5.8°$), and two narrow high-latitude emission spectra ($l^{\rm II}=350°$, $b^{\rm II}=+25°$ and $l^{\rm II}=11°$, $b^{\rm II}=+31°$, respectively).

The digital correlator was switched between left- and right-hand polarizations. These were recorded separately and later combined in the computer so that scans presenting both the difference between the two polarizations, as well as one of the polarizations alone, were obtained. The latter gave a comparison spectrum that was used in removing residual effects which had the absorption profile shape and were of the order of 1.1% for Cas A.

The absorption spectra of Cas A shows two widely separated components, one due to matter in the local spiral arm (Orion arm) and the other to matter in the Perseus spiral arm. The latter in turn shows two separated features with considerable structure in them.[1] For this reason, the Perseus arm feature has not been closely studied in the Zeeman experiments in the past. It was suspected that the arm showed many separate clouds (about eight to ten), and therefore, the resultant magnetic field splittings might be incomprehensibly mixed.

The Orion arm feature has been studied previously and the limit to the field, with no regard to possible structures or component clouds, was set as 4 μG.[2,3] This limit has been reduced in the present experiment to $+0.55\pm0.87$ μG. The data used in the work reported here were from one bank of 192 channels of the spectrometer operated with a 625-kHz overall bandwidth, i.e., 3.25 kHz/channel.

The data in the lower half of Fig. 1 show 16.3 hours' integration plotted as the difference between right- and left-hand polarization incident on the feed. Also shown is the absorption profile itself, obtained simultaneously. Zeeman splitting effects will manifest themselves as the derivative of the observed absorption lines, and predicted

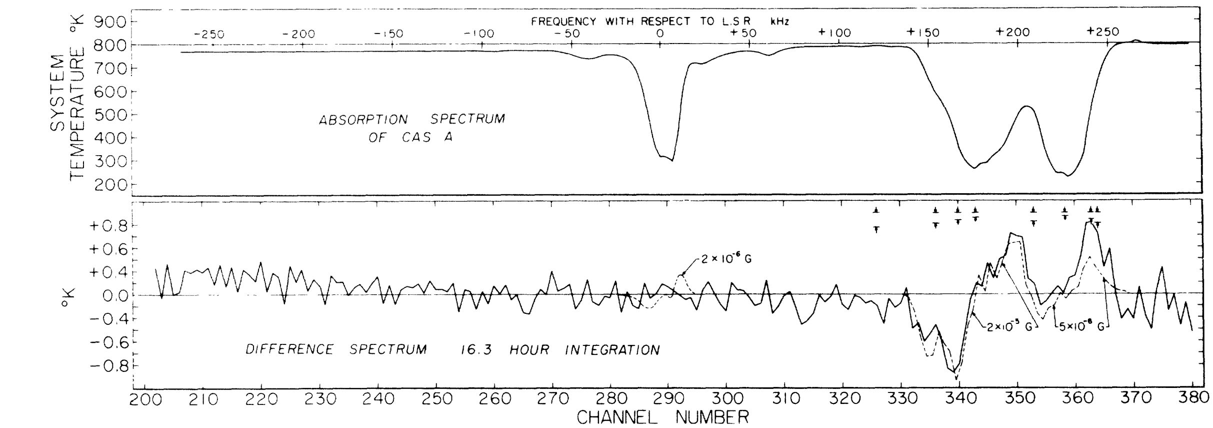

FIG. 1. The absorption spectrum of Cas A, together with the difference spectrum, right-hand minus left-hand polarization, incident on the feed representing 16.3 h of integration. Frequencies with respect to the local standard of rest are indicated. Arrowed bars represent expected peak-to-peak noise at various parts of the spectrum.

curves for various field strengths are shown in Fig. 1.

It is quite clear that while there is indeed no effect visible in the Orion arm feature, the Perseus arm feature shows a classic Zeeman splitting as predicted from theory for relatively simple spectral lines.

To illustrate the repeatability of the data, three separate and independent sets of data are shown in Fig. 2. These represent scans obtained over a period of ten days, from 30 April to 9 May 1968, and are all included in Fig. 1. The observing technique was to shift the local oscillator frequency every half-hour so that the spectral lines being observed would always appear in the same correlator channel. Any structure on

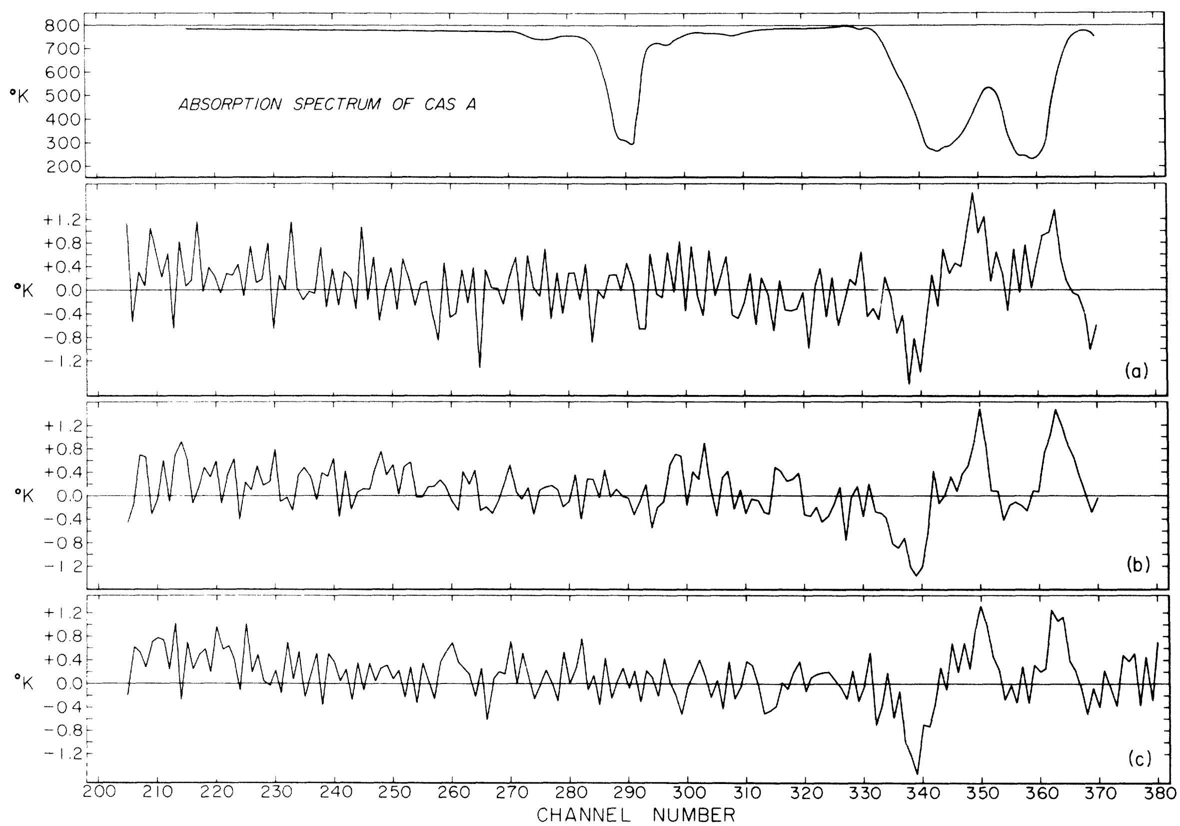

FIG. 2. Three independent sets of data on Cas A. (a) 3-h integration. (b) 4-h integration. (c) 7.5-h integration.

the rf bandpass of the system would then shift across the band during the observing run. In the case of Cas A, these shifts amounted to three channels between Figs. 2(b) and 2(c). No such effect can account for the signals seen in Figs. 1 and 2.

Alternatively, it might be argued that the structure is due to unknown effects in the correlator. This, too, is ruled out by examining Fig. 3, which shows a 6.5-h integration on a narrow emission line in the direction of HD 142096. The local oscillator frequency was only 28 kHz different from the Cas A runs with the same correlator bandwidth. Any peculiarities generated by the spectrometer should also be visible in these data. The increased noise on the Cas runs is, of course, due to the increase in the system noise from 180° off-source to 780° on-source.

We conclude that the strong effects seen in Fig. 1 are not spurious but must indeed be true Zeeman splitting of the absorption lines. The magnitude of the effect is at least 20 times the limit set to the Orion arm field. Furthermore, the splitting seems to be very simple in shape, which could be consistent with two separate fields in the two components in the Perseus arm. This is surprising in view of the apparently complex nature of the absorption profile, which has always been taken to suggest many component clouds when the 21-cm spectrum is closely examined.[1,4]

Goss,[5] observing in the OH line, has found four main components in this feature. They occur at +232, +219, +198, and +175 kHz with respect to the local standard of rest. We will not undertake a detailed analysis of these component fields at this stage, but will rather discuss the problem more generally.

Figure 1 shows that we can fit a relatively simple Zeeman pattern to the data which is closely related to the derivative of the absorption line, including the fine structure on it. This implies that all the "component clouds" suggested by the hydrogen-line data[4] or at very least the four suggested by the OH data[5] are permeated by very nearly identical fields. Without the OH data one might have to conclude that the fine structure in the H I spectrum is not indicative of so many "clouds" in view of this constraint.

Taking this double line in the H I profile as representing only two interstellar clouds, we find that the best-fit fields are -20.5 ± 3.0 μG for the -38-km/sec line (+180 kHz with respect to the local standard of rest) and -9.0 ± 3.0 μG for the deeper feature at -48 km/sec (+227 kHz). The negative sign indicates a field toward the observer. Errors quoted are two standard deviations.

Bringing the OH data back into the picture, we cannot easily escape the fact that four clouds are involved and that in their overlap region the Zeeman profiles will be confused. The lower frequency half of the component at +175 kHz and the higher frequency side of the component at +232 kHz will not suffer from overlap effects, and fitting the expected Zeeman profiles to the data, we find that these clouds contain fields of -19.0 ± 4.5 μG and -12.5 ± 2.0 μG, respectively. A first-order approach to fitting fields to the remaining two components shows that fields of this order must also be present. They also have the same signs. These results imply a field, directed toward the observer, in this part of the Perseus arm, which is at a distance of 2 to 3 kpc from the sun. This field is directed in an anticlockwise sense in the galaxy when viewed from the North Pole.

A preliminary reduction of part of the data on the emission spectra shows that limits of <10 μG can be set. The Taurus data are seven times as extensive as the Cas data described here, and show that a positive detection of +3 μG has been made in the deep feature at +10.8 km/sec. This result indicates a field directed away from the sun in the local spiral arm, i.e., also anticlockwise when viewed from the North Pole. These results will be fully reported elsewhere.

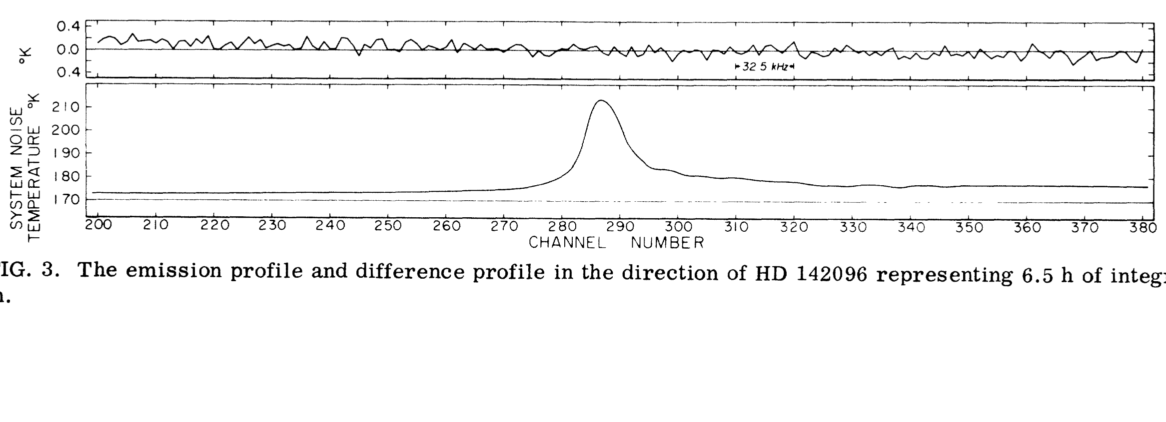

FIG. 3. The emission profile and difference profile in the direction of HD 142096 representing 6.5 h of integration.

Since the regions studied occur at galactic longitudes 350, 11, 111, and 184 deg, we cannot easily explain the absence of fields of 10 μG in the local arm as a selection effect. If spiral-arm magnetic fields are all similar and longitudinal, we might have expected a smaller field component in the Perseus arm than in the Orion arm at the longitude of Cas A. Since the reverse is true, the above two points suggest one of two conclusions: Either the sun is in a region of the galaxy with a low field strength, or the region in the direction of Cas A is unique. Rickard[6] has suggested that the latter might be so. He claims that a supernova occurred somewhere at the outer edge of the Perseus arm, which has distorted that arm to produce the double nature of the 21-cm emission spectra as well as of the optical lines. Shock waves, such as he envisaged, may have compressed and amplified the magnetic field so that we now see the amplified fields in this experiment.

An interesting aspect of this measurement is that either model may be easily checked. Since we are now dealing with fields of 10 μG and not 1 μG, the search for Zeeman effects in other absorption or emission spectra throughout the galactic plane will be made much easier.

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WILL THE RESONANCES ON THE LEADING TRAJECTORIES BECOME STABLE TO STRONG DECAY AT HIGH SPIN?

Hyman Goldberg
Department of Physics, Northeastern University, Boston, Massachusetts
(Received 1 July 1968)

A heuristic discussion is given of the decay modes of high-spin particles lying on a linearly rising trajectory. Among other things, it is concluded that for particles with masses $\gtrsim$3500 MeV ($J \gtrsim 12$), the total decay widths decrease with J and go to zero approximately like $(J \ln J)^{-0.28 J^{1/2}}$ as $J \to \infty$ ($0.28 = 2m_\pi b^{1/2}$, where $b \simeq 1$ GeV$^{-1/2}$ is asymptotic slope of the rising trajectory).

A simple relationship between the spin J and mass M (in GeV),

$$J = J_0 + M^2 \tag{1}$$

with $|J_0| < 1$, seems to characterize a number of families of baryonic[1] and bosonic[2] resonances. In the present communication we address ourselves to the consequences of Eq. (1) to the decay modes and widths of the higher resonances governed by it. The major conclusions, based on admittedly heuristic arguments, are the following: (1) After $J \sim 12$, the total widths of all resonances decrease fairly rapidly (but slower than $e^{-\alpha J}$). By $J = 50$ ($M^* \simeq 7$ GeV), the total widths of all "resonances" should be less than 1 MeV. (2) The dominant decay mode for $J \gtrsim 10$ is to a pion and a resonance with the highest kinematically allowed mass. Decays into the lowest mass states (e.g., $\pi\pi$) are predicted to vanish very rapidly for $J \geq 6$.

We shall consider only the two-body decay modes (these seem to be dominant if not exclusive) of a heavy particle of mass M and spin $J \simeq M^2$ into two particles which also lie on trajectories described by (1). With negligible error entailed in the ensuing arguments, J_0 will be taken equal to 0 in all cases, except when a pion may be involved.

The first part of the discussion is based on a result of wave equation theory; namely, centrifugal barrier effects will significantly inhibit a two-particle decay if

$$k^2 \ll l(l+1)/R^2, \tag{2}$$

where k is the c.m. momentum, R is the longest range of the hadronic force bewteen the decay products, and l is the orbital angular momentum of the final state. Since R is of the order of a