THE ASTROPHYSICAL JOURNAL, 291:716–721, 1985 April 15

MEASUREMENT OF SPIN TEMPERATURES IN A RAPIDLY MOVING H I SHELL

SHRINIVAS R. KULKARNI,[1] JOHN M. DICKEY,[2] AND CARL HEILES[1]
Received: 1984 August 22; accepted 1984 November 1

ABSTRACT

We have obtained high quality H I absorption spectra toward 3C 123 and 3C 147. For the normal-velocity H I we report two upper limits to magnetic field strengths and an upper limit to the spin temperature of the intercloud medium. Anomalous-velocity H I is present along both lines of sight. We find that this H I arises in a rapidly moving, large-angular-diameter H I structure. Emission and absorption properties of this H I are also anomalous. We find evidence suggesting that the H I structure is the result of collision of high-velocity clouds with the H I disk. We conclude by suggesting that the H I structure is post-shock gas that is cooling down.

Subject headings: interstellar: magnetic fields — radio sources: 21 cm radiation — Zeeman effect

I. INTRODUCTION

Recently Heiles (1983, 1984) has identified a remarkable H I structure in the galactic anti-center region. This structure is impressive on two counts: (1) Its angular size is very large (Fig. 1). It forms a nearly complete shell with an angular diameter $\sim 45°$ in longitude and $\sim 25°$ in latitude. (2) It is moving rapidly (velocity ≥ 70 km s^{-1}), since galactic rotation does not contribute significantly to radial velocity in this region of the sky.

In this paper, we discuss the results of high-quality H I absorption spectra toward two extragalactic sources, 3C 123 and 3C 147, both of which lie behind this structure (Fig. 1). We originally obtained these VLA spectra to measure magnetic-field strengths in diffuse clouds by utilizing the H I Zeeman effect. The details of the VLA observations are given in § II, and the Zeeman results are discussed in § III. As a by-product, we obtained significant lower limits to the spin temperature for the normal-velocity H I (§ IV).

The morphology of the structure resembles a shell quite strongly (Fig. 1) and *for this reason only* we will hereafter refer to this structure as the Anticenter Shell (ACS). In § V we analyze the ACS H I emission/absorption data and indeed find that the ACS H I has anomalous properties. In § VI we speculate on the origin of the ACS and conclude by favoring a model in which the ACS is the result of an encounter of a chain of high-velocity clouds with the H I disk.

II. THE VLA OBSERVATIONS

At the VLA, due to limitations imposed by the standard data-taking software, not all the antennas and both the polarizations are available for high-velocity-resolution observations. To overcome this limitation, we used instead the phased-array cross-correlating mode, the full details of which can be found in Kulkarni (1983).

Interstellar magnetic field splits the upper level of the 21 cm line. The transitions from these two upper levels to the ground state result in two lines of opposite circular polarization and separated in frequency by $2.8B$ (μG) Hz, where B is the magnetic field strength. For typical linewidths, the amplitude of the polarization-difference (i.e., Stokes V) spectrum is $\sim 0.2(B/3\ \mu\mathrm{G})$% of the peak absorption. Measurement of such a small difference requires accurate calibration of data and was achieved by the use of the VLA front-end "transfer switch," which enables the IF-electronic paths to be interchanged. Rapid operation of the transfer switch results in the two polarizations having the same IF bandpass shape, which simplifies calibration enormously.

The core-halo source 3C 123 was observed in the C-configuration (maximum baseline ~ 3 km) during 1982 February, and the compact source 3C 147 was observed during 1982 April in the A-configuration (maximum baseline ~ 30 km) of the VLA. The integration time and the effective flux were about 8 hr and 20 Jy in each case. For technical reasons, the innermost six antennas were left out. This also prevented H I emission fringes from polluting the absorption spectra. A bandwidth of 0.78125 MHz and 256 channels was employed. In addition to the polarization switching, the sky frequency was switched by 0.8 MHz in order to perform bandpass correction. For the 3C 123 observations, observations of the "ON 21 cm line" band and the "OFF 21 cm line" band were alternated every 8 minutes. In contrast, for 3C 147 only 8 minutes was spent on the OFF frequency for every 24 minutes of ON frequency observations.

III. MAGNETIC FIELD STRENGTHS TOWARD 3C 123 AND 3C 147

Applying the least squares fit program of Troland and Heiles (1982) to the Stokes V data, we place a conservative upper limit (the absolute value derived for B plus 3 times the mean error; cf. Troland and Heiles 1982) of 11 μG in the 5 km s^{-1} deep absorption feature toward 3C 123. This feature arises in the thin part of the Taurus dust cloud, which has been modeled as a sheet containing a molecular core ($n \sim 800$ cm^{-3}) and an atomic halo sheet ($n \sim 90$ cm^{-3}) (Crutcher 1980); here n is the particle density. Crutcher, Troland, and Heiles (1981), using Arecibo OH absorption data, have placed an upper limit of 25 μG for the molecular core.

Toward 3C 147 we place a limit of about 22 μG for the entire feature. No molecules have been reported in this direction, and hence the features presumably arise in diffuse clouds for which we assume the standard pressure of $nT \sim 3700$ cm^{-3} K (Myers 1978). With a spin temperature of ~ 60 K for the deep absorption features, $n \sim 65$ cm^{-3}.

Are our results compatible with the expected relation

[1] Department of Astronomy, Univ. of California, Berkeley.
[2] Department of Astronomy, Univ. of Minnesota, Minneapolis.

1985ApJ...291..716K

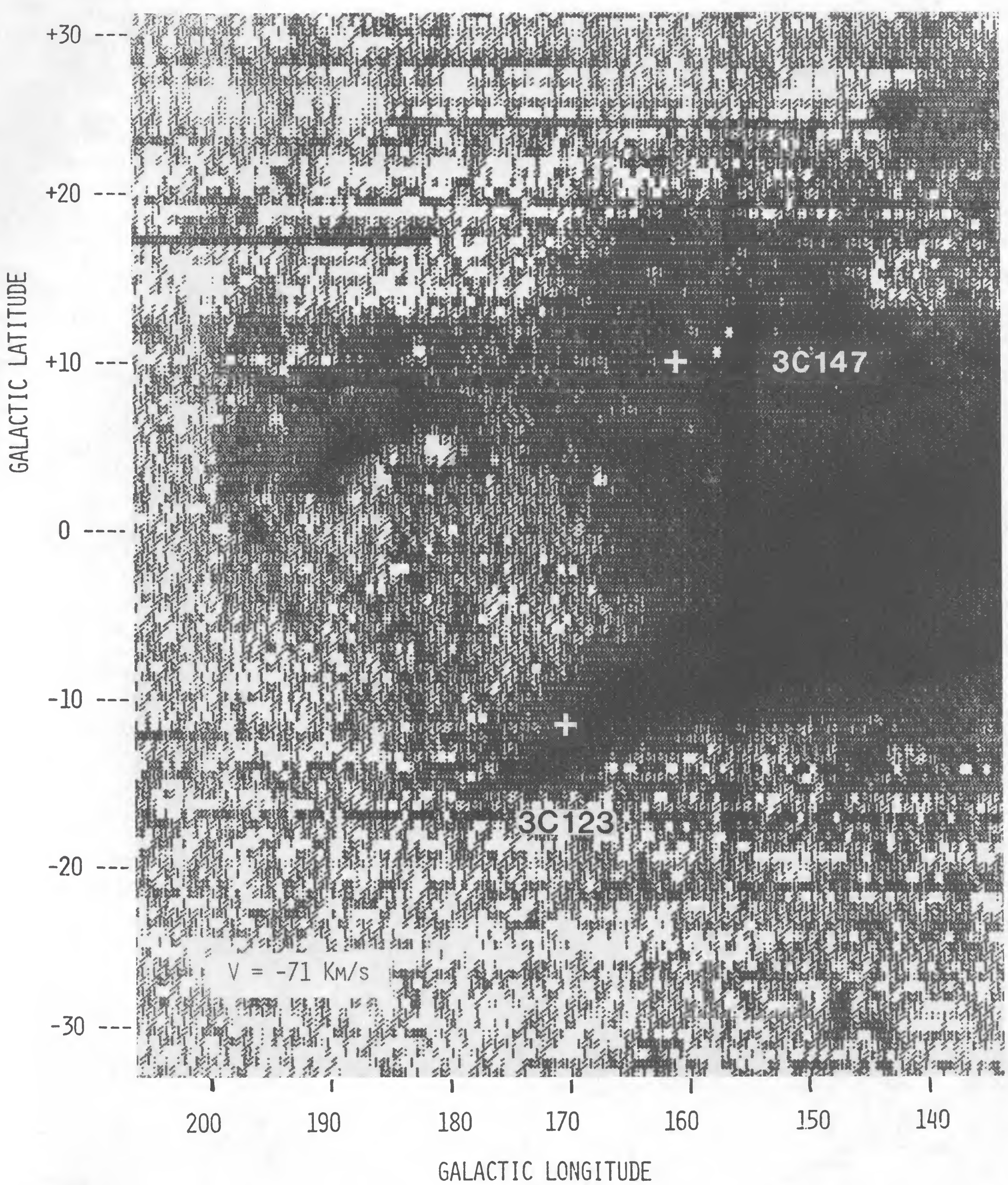

FIG. 1.—Map of the anticenter region in a 6 km s^{-1} velocity interval centered at -71 km s^{-1}. The ACS is the shell-like structure centered at $l \approx 180°$ and $b \approx -5°$. The positions of 3C 123 ($l = 170°.6$, $b = -11°.6$) and 3C 147 ($l = 161°.7$, $b = 10°.3$) are marked by crosses.

between n and B? Assuming flux-freezing, the expected B is given by

$$B = B_i(n/n_i)^{\kappa} \quad \text{and} \quad \tfrac{1}{3} < \kappa < \tfrac{1}{2}\,, \tag{1}$$

where B_i and n_i are the initial values of magnetic field strength and density, assumed to be 3 μG and 1 cm^{-3} respectively (Mouschovias 1976). The restriction of κ in equation (1) applies for typical three-dimensional *collapses.* Our 3 σ upper limits to B in both directions are inconsistent with the predictions of equation (1). It is possible that equation (1) is indeed valid and that the interstellar magnetic field is unfavorably oriented *in both directions.* However, as Mouschovias and recently Fleck (1983) have stressed, equation (1) is not applicable to diffuse clouds because they are not self-gravitating clouds. Our limited data show the same behavior as the more extensive data of Troland and Heiles (1982, 1985) which are based on H I emission studies, despite the fact that H I absorption studies are biased to cold, high-density regions whereas H I emission studies are unbiased.

If equation (1) does not determine B, then what does determine B? Troland and Heiles (1985) argue that the field strength in diffuse clouds is determined by the (hydromagnetic) shock history of the cloud. At least in the case of 3C 123, this suggestion seems eminently reasonable, because the Taurus dust complex is really a sheet (Crutcher 1980)—indicating that the magnetic field may have played a role in guiding the compression of the dust cloud.

IV. SPIN TEMPERATURE OF NORMAL-VELOCITY WARM H I

As a by-product of the Zeeman-splitting observations, we obtained sensitive absorption spectra. The absorption spectrum of 3C 123 consists of distinct features at ~ -60 km s^{-1}, -20 km s^{-1}, 5 km s^{-1}, and 20 km s^{-1} (Fig. 2a). Here we discuss the H I in the "saddle region" between -7 km s^{-1} and -13 km s^{-1}. This H I is interesting because it appears to be unrelated to the two clouds at $v = 5$ km s^{-1} and $v = -20$ km s^{-1} and hence may be interpreted to be the intercloud medium.

After accounting for stray radiation (Mebold *et al.* 1982), $\langle T_B \rangle$, the mean emission brightness of the H I in the saddle region is 7.5 K. No absorption is detected in any channel in the saddle region despite a low σ_τ of 0.8×10^{-3}; here σ_τ is the single-channel optical-depth rms noise. Thus the 3 σ lower limit on T_s, the single-channel spin temperature, is $\sim$3000 K. The mean absorption of the saddle H I is $\langle \tau \rangle = (1 \pm 2.3) \times 10^{-4}$, leading to a more stringent 3 σ lower-limit: $\langle T_s \rangle \sim 10^4$ K.

Measurement of high spin temperatures is a difficult observation and should have an independent confirmation, perhaps with a bandwidth twice as large as ours. Not only should the radiometer noise be low, but the baseline has to be well defined. The sequence and duration of the ON and OFF observations for the 3C 123 run (§ III) led to an excellent determination of the baseline (albeit at the expense of increased radiometer noise). In order to assess the reliablity of our baseline, we compared our spectrum with a similar VLA spectrum of Liszt, Dickey, and Greisen (1982, hereafter LDG). The LDG spectrum is of lower sensitivity ($\sigma_\tau \sim 2.5 \times 10^{-3}$) but has the advantage of covering twice the bandwidth, which ensures a more reliable determination of the baseline. Our baseline agrees with the LDG baseline to within the noise of the LDG spectrum. Also, the LDG lower limit on $\langle T_s \rangle$ is $\sim$3000 K—in agreement with our *single channel* lower limit.

Our VLA spectrum and the LDG data do not agree with the Arecibo single-dish determinations of Payne, Salpeter, and Terzian (1982) and Dickey, Salpeter and Terzian (1978, hereafter DST). After accounting for a baseline error they find $\langle \tau \rangle = (6 \pm 0.4) \times 10^{-3}$ and $(2.7 \pm 0.4) \times 10^{-3}$ respectively. In general, interferometric absorption spectra are more reliable than single-dish spectra; in particular, single-dish spectra suffer from variations in H I emission, contamination of the "OFF source" spectra by the response of the side lobes to the source,

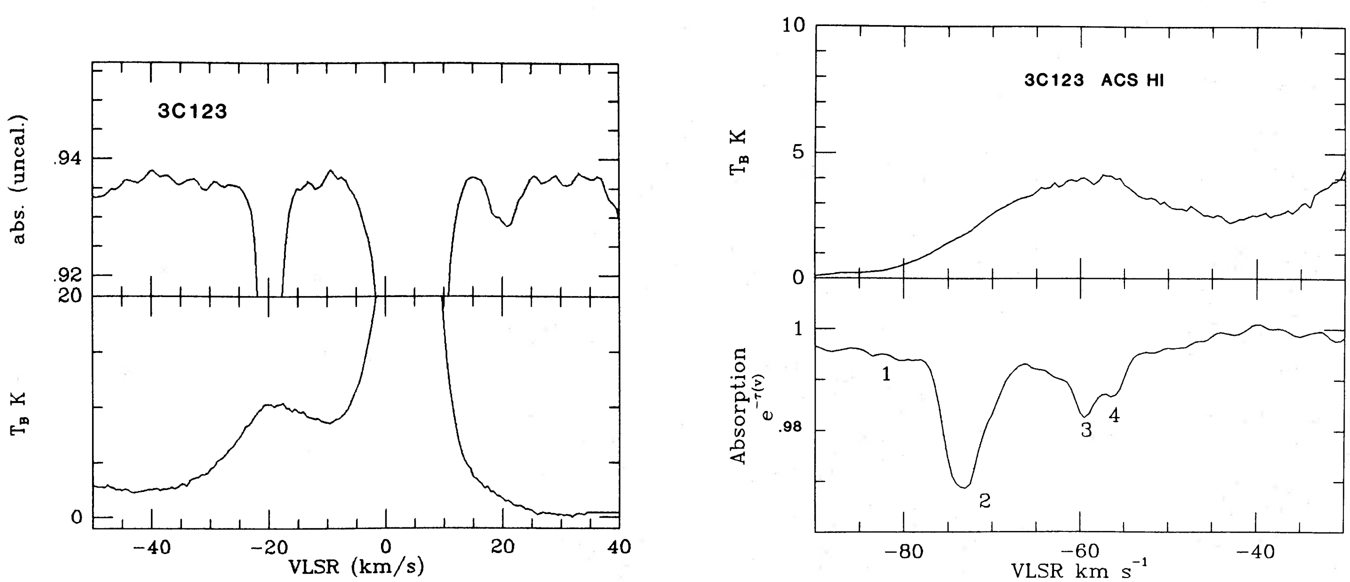

FIG. 2a. FIG. 2b.

FIG. 2.—Arecibo H I emission spectrum (channel separation 0.17 km s^{-1}) and VLA H I absorption [i.e., $e^{-\tau(v)}$] spectrum toward 3C 123: (*a*) Normal H I velocity range. Note that the displayed absorption spectrum is the uncalibrated bandpass-corrected spectrum. (*b*) ACS H I velocity range. The emission data have been supplemented outside $|v| > 66$ km s^{-1} from published data (DST).

and finally are more prone to baseline instabilities. This may explain the disagreement.

To sum up, we report here a lower limit of 10^4 K to the spin temperature of warm H I in the direction of 3C 123. However, for the reasons mentioned earlier in this section the measurement of such high spin temperatures is quite difficult, and hence additional confirmatory observations are needed. The temperature of warm H I is an important parameter in understanding the heating and cooling processes in the interstellar medium. We now summarize and compare previous determinations of this temperature with our lower limit. In particular we wish to point out that there are indications that the spin temperature of warm H I is possibly higher than the value of 8000 K which is expected on theoretical grounds. Kalberla, Mebold, and Reich (1980) find $T_s \sim 6000$ K and ~ 2850 K toward Cyg A ($b = 5°.8$) and Cas A ($b = -2°.1$) respectively. At such low latitudes, considerable contribution from cooler clouds located along the line of sight can be expected; this is turn biases the measured T_s of warm H I to lower values. Payne, Salpeter, and Terzian (1983, hereafter PST83) find that the harmonic mean spin temperature of the local, independently-distributed, not-strongly-absorbing (NSA) H I is ~ 5000 K. Again this should be considered a lower limit, because some of the NSA H I may arise from low-column-density cold clouds. And finally, in the solar neighborhood, observations of the solar He $\lambda 584$ photons and H Lyα indicate temperatures of $(1.2 \pm 0.3) \times 10^4$ K and $< 1.7 \times 10^4$ K (Weller and Meier 1981) respectively.

As an aside, we note that a crude Gaussian decomposition of the emission profile shows that the saddle H I is part of a wide (FWHM ≈ 28 km s^{-1}) component with a column density of $\sim 5 \times 10^{20}$ cm^{-2}. This FWHM is not inconsistent with our lower limit on $\langle T_s \rangle$ of 10^4 K.

V. PROPERTIES OF ACS H I

The emission/absorption spectra of the ACS H I toward 3C 123 and 3C 147 are shown in Figures 2*b* and 3 respectively. The 3C 123 ACS H I absorption spectrum has been decomposed into four Gaussian components (Table 1). In Table 1, τ_0 is the central optical depth of the Gaussian component centered at velocity v_0 and an rms velocity width of σ. T_d is the kinetic temperature of the gas obtained by assuming that the width of the absorption feature is entirely thermal in origin.

The estimation of T_B, the emission brightness corresponding to each Gaussian component (Col. [6]) is not straightforward for two reasons. First, the narrower components 2, 3, and 4 do not distinctly appear in the emission spectrum. Second, the emission data toward ACS H I indicate angular structure finer than the 3'.2 Arecibo beam (Payne, Salpeter, and Terzian 1980). Spatial mapping of high-velocity H I complexes, similar to the ACS, has led to the picture that small-σ features arise in cold,

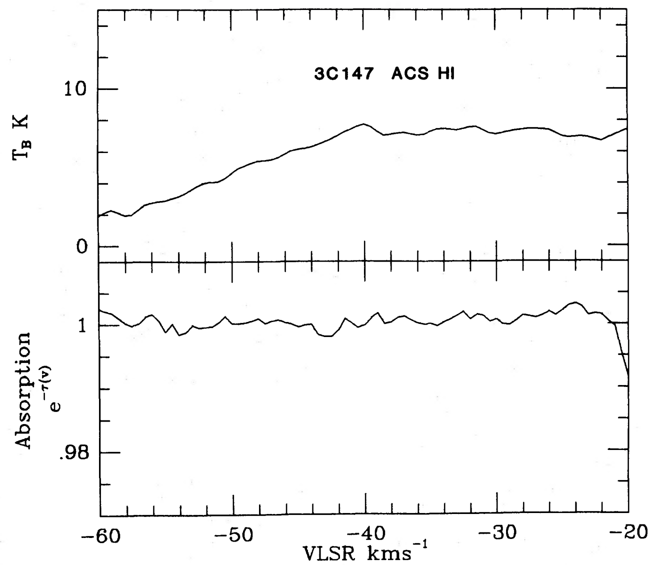

FIG. 3.—Green Bank 300 foot (91 m) telescope H I emission spectrum (channel separation 1.37 km s^{-1}) and VLA absorption spectrum of ACS H I in the direction of 3C 147. The absorption spectrum shown here has a second-order baseline removed from the spectrum after the empirical bandpass correction.

small-diameter cloudlets which are immersed in a larger σ, warmer, and widely distributed intercloudlet medium (Schwarz and Oort 1981; Payne, Salpeter, and Terzian 1980). Identifying component 1 as the intercloudlet medium, we see that $T_B(\max) \approx 4$ K. $T_B(\max)$ for the small-σ features has been estimated by noting that (*a*) $T_s \leq T_d$, and (*b*) $T_B = T_s\,(1 - e^{-\tau_0})$. Due to turbulence, $T_d > T_{cl}$, the cloudlet temperature; for local diffuse clouds, $T_d/T_{cl} = 1.7$ (PST83). T_{cl} estimated thus along with $T_{cl}(\tau)$—an independent estimate using the T_{cl}–τ relation (PST83)—are given in columns (7) and (8). For components 3 and 4, $T_{cl}(\tau) > T_{cl}$, whereas the opposite seems to be the case for component 2. A careful look at Figure 2 shows that component 2 may be a blend of two or more narrower features. Such blends increase T_d without significantly affecting $T_{cl}(\tau)$.

In summary, both the narrow and the wide absorption components have properties quite different from those of local H I clouds:

a) Absorption is detected over the entire velocity range, and the maximum spin temperature is less than 400 K. In contrast, the spin temperature of 50% of local H I is above 500 K, and hence considerable portion of local H I is undetectable in absorption (DST).

b) The cloudlets appear to be cooler than that expected on the basis of the T_{cl}-τ relation.

c) The intercloudlet medium is quite unusual as well. Unlike the normal intercloud medium (§ IV), it has a moderate spin

TABLE 1

GAUSSIAN COMPONENTS OF THE ACS H I IN ABSORPTION TOWARD 3C 123

Component (1)	v_0 (km s^{-1}) (2)	$\tau_0 \times 10^3$ (3)	FWHM $\sigma\sqrt{\ln 256}$ (km s^{-1}) (4)	T_d (K) (5)	T_B(max) (K) (6)	T_{cl} (K) (7)	$T_{cl}(\tau)$ (K) (8)	N_H(max) (10^{-18} cm^{-2}) (9)
1.........	−70.0(:)	7(:)	35.0(:)	26719	4	<360	...	255
2.........	−73.1 ± 0.05	23 ± 1	4.7 ± 0.09	477	11	280	198	93
3.........	−59.3 ± 0.14	10 ± 1	3.7 ± 0.20	327	3.3	192	263	6
4.........	−55.9 ± 0.14	7 ± 1	2.1 ± 0.18	98	0.7	57	297	3

temperature ($T_s < 360$ K) and an apparent velocity dispersion of ~ 15 km s^{-1}. This gas is extremely supersonic if the velocity dispersion arises from random motions.

The properties of the ACS H I toward 3C 147 (Fig. 3) are quite different from that toward 3C 123: we did not find any narrow absorption features despite a low σ_τ of 0.8×10^{-3}. For any possible large-σ absorption feature, we adopt the lower limit of 2000 K of Mebold *et al.* (1982) because of the uncertainty in the baseline of the spectrum in Figure 3. The observing procedure for 3C 147 (§ II), unlike 3C 123, maximized sensitivity towards the Zeeman experiment at the expense of accurate bandpass correction. A corollary of the T_s–τ relation (cf. PST83) is the τ–T_B relation, from which we predict $T_s = 300 \pm 100$ K (the uncertainty reflects real variations and not the much smaller measurement errors) for the observed T_B of 7 K. Instead, the observed $T_s > 2000$ K makes the ACS H I toward 3C 147 unusual as well (Fig. 4). Also note the peculiar plateau-like shape and the unusual sloping edge of the emission profile (Fig. 3).

VI. THE ORIGIN OF THE ACS

The origin of the ACS is unclear. In fact, from the H I data alone, it is not clear whether the ACS is a moving H I ring or an expanding H I shell. The nearly complete shell is easily recognized at a radial velocity v as extreme as -90 km s^{-1}, the negative-velocity limit of Heiles's (1983) data. For $0 > v \geq -40$ km s^{-1}, the ACS is confused with the much stronger normal-velocity H I. An expanding H I shell model may be understood in terms of a supernova or stellar-wind origin or both, and hence might be more appealing than a moving H I ring model. Despite the appeal, there are two problems with the shell model:

a) Since we are only sensitive to the radial velocity, the shell expansion speed, V_{sh}, is greater than 90 km s^{-1}. Even this (minimum) V_{sh} makes the ACS a very unusual H I, shell since in Heiles's (1979) catalog of shells and supershells, the maximum V_{sh} is 25 km s^{-1}.

b) The ACS does not seem to satisfy certain basic criteria expected of an expanding shell. The apparent size of an expanding shell, as measured in isovelocity maps, should change with velocity: (i) at $v = \pm V_{sh}$, the "polar cap" region should be visible; (ii) at $v = 0$ km s^{-1}, the shell should have the largest apparent size; and finally, (iii) the shell structure should be seen at positive velocities as well. Heiles (1983) does not find any significant change of the shell size with velocity for $-40 > v > -90$ km s^{-1}, nor is there any trace of a shell seen for $0 < v < 100$ km s^{-1}. Point (iii) is not too disturbing, since *none* of the shells and supershells cataloged by Heiles (1979) are two-sided. Kulkarni (1983), using the Bell Telephone Laboratory H I survey (Stark *et al.* 1985), finds that the shell disappears for $v > 100$ km s^{-1}. Instead he finds that a chain of classical high-velocity clouds (AC I, AC II, etc.) are present in the same region of sky occupied by the shell. Mirabel (1982) finds a perturbation in the kinematics of the intermediate-velocity ($-40 > v > -100$ km s^{-1}) H I in the vicinity of $(l, b) = (185°, -11°)$ and attributes this intermediate H I to the interaction of the high-velocity clouds (HVC) with the H I in the disk. *It is precisely this intermediate-velocity* H I *which forms the* ACS.

The conjecture that the ACS is a "cosmic splatter" is strengthened by the following two findings:

a) The ACS is one-sided (i.e., the shell is seen only at negative velocities and is absent at positive velocities). Indeed, this is what is expected of a disturbance created by the collision of HVCs with the disk H I.

b) Kulkarni and Mathieu (1984) have attempted to obtain the distance to the ACS by searching for anomalous-velocity interstellar Ca K absorption lines in the spectra of early-type stars located in the direction of the ACS. They report the absence of any anomalous Ca K absorption lines toward 17

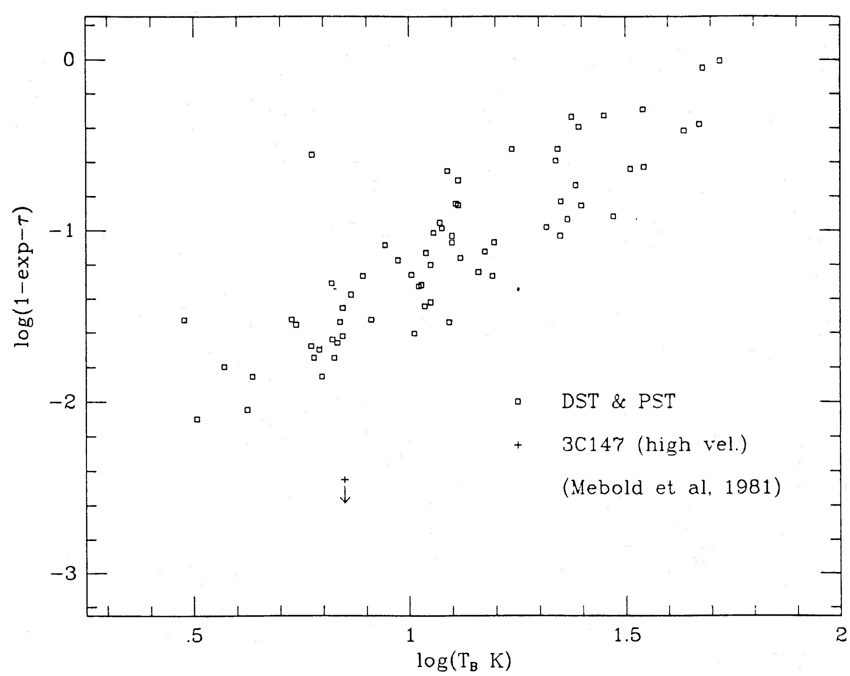

FIG. 4.—The ACS H I absorption feature in the 3C 147 direction superposed on the τ-T_B curve for local H I. Here we have used the upper limit of Mebold *et al.* (1982) for τ. Despite this upper limit, it is clear that the ACS H I in this direction is different from local H I.

stars with distances ranging from 100 pc to 2500 pc. Barring some unusually low Ca II abundance, they conclude that the ACS is beyond 2.5 kpc; in fact, the gas-phase abundance of Ca is expected to be higher than normal in shocked gas. Thus the expected size of the ACS is ~ 1 kpc, and the total kinetic energy of the ACS is $\sim 10^{53}$ ergs. Under the "cosmic-splatter" hypothesis, the distance to the ACS has been estimated to be between 2 kpc and 5 kpc (Mirabel 1982); the estimate follows from knowing the scale height of disk H I and the latitude at which the high-velocity H I seems to show interaction with lower-velocity H I. The uncertainty in the distance arises from our ignorance of the z-height at which the high-velocity clouds first start extensive interaction with the normal-velocity H I.

Both these data are difficult to reconcile with a supernova/stellar-wind origin for the ACS. Thus while there is no absolutely conclusive evidence for the cosmic-splatter hypothesis, it is fair to say that all the available data are consistent with this hypothesis.

In the context of the cosmic-splatter model it is attractive to consider that the ACS H I is post-shock gas cooling down, the shock created in the first place by collision of high-velocity clouds with the galactic disk. The unusual properties of the ACS H I (§ V) may then be attributed to shocked H I. However, this is not a unique interpretation, since the temperature of H I depends on a host of parameters such as the ambient pressure, radiation field, cosmic-ray density, depeletion of metals, time-dependent events, etc. Even after accepting the cosmic-splatter model, there are a couple of questions to be answered:

1) Can post-shock models explain successfully the anomalous properties of the ACS H I?

2) The line of sight to 3C 123 lies near the inner edge of the ACS, whereas that of 3C 147 lies near the outer edge (Fig. 1). Is there any connection between this fact and the completely different nature of H I at these two points (§ V)?

Unfortunately, the 21 cm line is not a good probe of shocked regions. Hence additional diagnostics, especially UV absorption lines (which would also determine the distance to the ACS), are urgently needed to understand the ACS. If the ACS is truly a cosmic splatter, then we have a very good case study of a supershell formed by the interaction of high-velocity clouds with the galactic H I disk.

We thank H. Liszt for providing the LDG absorption spectrum of 3C 123. The VLA and the 300 foot (91 m) radio telescope at Green Bank are operated by the National Radio Astronomy Observatory under contract from the National Science Foundation. J. D.'s research is supported in part by the following grants: (1) NSF grant AST 82-168 to the University of Minnesota; (2) a grant from the Graduate School, University of Minnesota; and (3) a grant from the Alfred P. Sloan Foundation. C. H. and S. K.'s research is supported in part by NSF grant AST 82-12058 to the University of California, Berkeley.

REFERENCES

Crutcher, R. M. 1980, *Ap. J.*, **239**, 549.
Crutcher, R. M., Troland, T. H., and Heiles, C. 1981, *Ap. J.*, **249**, 134.
Dickey, J. M., Salpeter, E. E., and Terzian, Y. 1978, *Ap. J. Suppl.*, **36**, 77 (DST).
Fleck, R. C. 1983, *Ap. J.*, **264**, 139.
Heiles, C. 1979, *Ap. J.*, **229**, 533.
Heiles, C. 1983, in *Kinematics, Dynamics and Structure of the Milky Way*, ed. W. L. H. Shuter, (Dordrecht: Reidel), p. 105.
Heiles, C. 1984, *Ap. J. Suppl.*, **55**, 585.
Kalberla, P. M. W., Mebold, U., and Reich, W. 1980, *Astr. Ap.*, **82**, 275.
Kulkarni, S. R. 1983, Ph. D. Thesis, University of California, Berkeley.
Kulkarni, S. R., and Mathieu, R. 1984, *Proc. 3d Asian-Pacific Regional IAU Conf. Kyoto*, submitted.
Liszt, H. S., Dickey, J. M., and Greisen, E. W. 1982, *Ap. J.*, **261**, 102 (LDG).
Mebold, U., Winnberg, A., Kalberla, P. M. W., and Goss, W. M. 1982, *Astr. Ap.*, **115**, 223.
Mirabel, I. F. 1982, *Ap. J.*, **256**, 112.
Mouschovias, T. Ch. 1976, *Ap. J.*, **207**, 141.
Payne, H. E., Salpeter, E. E., and Terzian, Y. 1980, *Ap. J.*, **240**, 499.
———. 1982, *Ap. J. Suppl.*, **48**, 199.
———. 1983, *Ap. J.*, **272**, 540 (PST83).
Schwarz, U. J., and Oort, J. H. 1981, *Astr. Ap.*, **101**, 305.
Stark, A. A., Bally, J., Linke, R. A., and Heiles, C. 1985, in preparation.
Troland, T. H., and Heiles, C. 1982, *Ap. J.*, **252**, 179.
———. 1985, in preparation.
Weller, C. S., and Meier, R. R. 1981, *Ap. J.*, **246**, 386.

JOHN DICKEY: Dept. of Astronomy, Univ. of Minnesota, 116 Church St. S.E., Minneapolis, MN 55455

CARL HEILES and SHRINIVAS KULKARNI: Dept. of Astronomy, Univ. of California, Berkeley, CA 94720