THE ASTROPHYSICAL JOURNAL, 267:174–178, 1983 April 1

SHOCK FORMATION OF HCO^+

MOSHE ELITZUR
Department of Physics and Astronomy, University of Kentucky
Received 1982 March 22; accepted 1982 September 17

ABSTRACT

It is shown that shocks propagating in dense molecular regions will lead to a decrease in HCO^+ relative abundance, in agreement with previous results by Iglesias and Silk. The shock enhancement of HCO^+ detected in the supernova remnant IC 443 by Dickinson *et al.* is due to enhanced ionization in the shocked material. This is the result of the material penetrating the remnant cavity where it becomes exposed to the trapped cosmic rays. A similar enhancement appears to have been detected by Wootten in W28 and is explained by the same model.

Subject headings: interstellar: molecules — nebulae: supernova remnants — shock waves

I. INTRODUCTION

Lately, studies of abundances in shocked interstellar gases have attracted some attention because, for certain species, the chemistry in these high temperature regions can differ significantly from that in the bulk material of clouds. The identification of such species can provide explanations for observed unusual abundances. Notable examples are CH^+ in diffuse clouds (Elitzur and Watson 1978) and H_2O (Elitzur 1979*a*) and SiO (Hartquist, Oppenheimer, and Dalgarno 1980) in dense clouds. Conversely, one can use unusual abundances as shock diagnostics.

During the course of an attempt to identify shock signatures, Dickinson *et al.* (1980) discovered that the abundance ratio HCO^+/CO in the shocked material associated with the supernova remnant IC 443 was enhanced in comparison with the unshocked gas by almost 100. More recent observations by DeNoyer and Frerking (1981) support the finding of a shock enhancement for HCO^+/CO, although the number they quote is about 3 to 10 times smaller than the one by Dickinson *et al.* (1980). These observations are in direct conflict with the calculations of Iglesias and Silk (1978) which predict a decrease in HCO^+ abundance behind shocks in dense clouds (CO abundance is probably unaffected by shock waves, unless they are so strong as to dissociate all molecules). Because of the central role of HCO^+ in the ion-molecule scheme (Herbst and Klemperer 1973; Watson 1976), this conflict is of some concern.

The problem appears to have been partially alleviated by the observations of Rodriguez Kuiper and Dickinson (1980). These show that other shocked regions do not exhibit HCO^+ enhancement and that IC 443 is thus somewhat unique in its behavior. The present paper will attempt to identify the reasons for this exceptional behavior of IC 443.

II. GENERAL CONSIDERATIONS

In molecular regions, HCO^+ is produced efficiently via the reaction

$$H_3{}^+ + CO \rightarrow HCO^+ + H_2 \,. \tag{1}$$

Because virtually every cosmic ray ionization of H_2 leads to $H_3{}^+$ production, the HCO^+ abundance is directly related to the cosmic ray ionization rate (e.g., Watson 1976; see also Prassad and Huntress 1980). If charges are introduced into the cloud by cosmic ray ionizations and removed by dissociative recombination, than the relative electron abundance X_e obeys, using standard cosmic ray ionization rate,

$$X_e \approx 10^{-5}\,(\mathrm{cm}^{-3}/n)^{1/2}\,, \tag{2}$$

which is decreasing with density. In dense clouds, the HCO^+ relative abundance should therefore vary with density like $n^{-1/2}$. This appears to be the explanation for the results of Iglesias and Silk. Indeed, their chemistry did not contain any temperature-dependent reactions which could affect the production of HCO^+. Furthermore, its postshock abundance seems to follow the overall density in the manner just described.

The production of HCO^+ in diffuse regions proceeds mainly via

$$CO^+ + H_2 \rightarrow HCO^+ + H \tag{3}$$

and

$$C^+ + H_2O \rightarrow HCO^+ + H \tag{4}$$

(e.g., Prassad and Huntress 1980; see also Mitchell, Ginsburg, and Kuntz 1978). With the chemical composition of diffuse clouds these processes are not as efficient as the production mechanism in dense regions (eq. [1]). The result is that in dense, primarily molecular, clouds, HCO^+ is a major ion, and perhaps even the major ion. In contrast, it is rather inconspicuous in diffuse, and mainly atomic, regions.

An examination of all the reactions involved in HCO^+ production and destruction (e.g., Prassad and Huntress 1980) reveals that none of the rate coefficients is temperature dependent. A possible exception is

$$O + CH \rightarrow HCO^+ + e , \quad (5)$$

which has a rather weak temperature dependence (probably like $T^{0.44}$) and which is not expected to be a significant source of HCO^+ under reasonable circumstances anyhow. An enhancement of HCO^+ abundance behind a shock front therefore cannot be explained by high temperature chemistry like that of the shock-enhanced species mentioned above. Instead, there are two possible explanations for the observed enhancement in IC 443: (1) The shock runs into a low density region with the chemical composition of a diffuse cloud. As a result of the postshock compression, the shocked gas is dense enough that its chemistry changes to that of a dense, molecular region. HCO^+ abundance is then enhanced across the shock front. (2) The shock propagates in a primarily molecular region, but the fractional ionization increases across the shock front to a value which is higher than that obtained by standard cosmic ray ionization (eq. [2]). This can happen if the shock front is the boundary between an ordinary cloud and a region where the cosmic ray ionization rate is enhanced for some reason.

Possibility (1) was advocated recently by Mitchell and Deveau (1982) and will be investigated first.

III. LOW DENSITY PRESHOCK GAS

If the preshock gas is to have the chemical composition of a diffuse region, then its density has to be below the value of the transition to primarily molecular content. Most calculations show that this transition occurs at a density of a few hundreds cm^{-3}. For instance, one of the more recent calculations (by Mitchell, Ginsburg, and Kuntz 1978) shows that at optical depth one and density of $\sim$ 300 cm^{-3}, carbon will be roughly equally divided among its atomic and molecular forms. At densities exceeding $\sim$ 1000 cm^{-3}, more than 90% of the carbon will be in CO. Mitchell and Deveau (1982) have therefore suggested that IC 443 is exceptional because the shock runs into a very low density cloud, with a density of only 100 cm^{-3}. In view of the above, this choice of density is crucial to their model.

It appears, however, that this idea is in conflict with observations. The supernova explosion that originated IC 443 occurred most certainly in a region of enhanced density, on the periphery of an extensive molecular complex (e.g., Giovanelli and Haynes 1979). The molecular preshock gas was observed in ^{12}CO by Scoville *et al.* (1977) and by Cornett, Chin, and Knapp (1977). Both groups were in agreement that the density is most likely in the range of 300–1000 cm^{-3}, with preference given to the higher end. A problem with these density estimates is that they have to rely on radiative transfer models with a relatively large number of uncertain parameters because the ^{12}CO line is optically thick. Although the optical thickness of the ^{12}CO line is in itself indicative of high densities, a more reliable density estimate would have to involve optically thin transitions, such as those of ^{13}CO, for instance. Cornett *et al.* have actually managed to detect the ^{13}CO but did not perform extensive observations of it.

Extensive observations of the molecular preshock gas toward IC 443 were performed recently by DeNoyer and Frerking (1981) who detected, among other molecules, the ^{13}CO as well. The observed ground state column density of ^{13}CO is 2×10^{15} cm^{-2}, and if the excitation temperature is 10 K, then the total ^{13}CO column density is $\sim 8 \times 10^{15}$ cm^{-2} (L. K. DeNoyer, private communication). For higher excitation temperatures, in the range 50–100 K, the corresponding column density increases to $2\text{–}3 \times 10^{16}$ cm^{-2}. With reasonable estimates for the cloud dimensions, $\sim$1–2 pc, this leads to an estimate of 1000–2000 cm^{-3} for the overall density of the molecular preshock gas (L. K. DeNoyer, private communication).

Recent observations by Plambeck and collaborators (Plambeck 1982) led to the detection of strong emission in the $J = 2 \rightarrow 1$ line of CO. The inferred preshock density from the ratio of the two detected CO lines is also a few thousand cm^{-3}. This density estimate is thus consistent with all the molecular line observations toward IC 443. It is evident that a density of only 100 cm^{-3} cannot be considered a reasonable estimate for the preshock gas.

One may argue that although the ambient density is much higher than 100 cm^{-3}, the material may still be predominantly atomic since the chemistry in the transition region is rather uncertain and varies considerably with various properties of the cloud. It is useful, therefore, to compare the density of IC 443 with that of the other shock regions where HCO^+ enhancement does not exist according to Rodriguez Kuiper and Dickinson. In particular, comparisons of column densities, especially of ^{13}CO when available, are more meaningful because their estimates are more reliable.

a) *W44*

This is also a supernova remnant (SNR). The H I emission from the source (Knapp and Kerr 1974) is dominated by the shocked material. Its column density is only 1.5×10^{20} cm^{-2}. Cornett and Hardee (1975) estimate that the average preshock density is ~ 10 cm^{-3}. However, it appears that in a certain direction the expanding shell runs into a molecular cloud similar to the case of IC 443. Wootten (1977) observed the CO emission from this region. He estimates a peak postshock ^{13}CO column density of $\sim 10^{16}$ cm^{-2} and a preshock density of $\sim 10^3$ cm^{-3}. Both estimates are similar to IC 443.

b) *NGC 281*

Elmegreen and Lada (1978) performed both ^{12}CO and ^{13}CO observations of this H II region. Assuming that the excitation temperatures of both species are the same and determined from ^{12}CO to be 10–15 K, the ^{13}CO

column density is 1.6×10^{16} cm^{-2} at one emission peak and 3×10^{15} cm^{-2} at the other. The inferred total densities are 760 and 160 cm^{-3}, respectively.

c) GL 490

This region exhibits molecular emission which covers a velocity range of ~ 60 km s^{-1}. Lada and Harvey (1981) observed it in both CO isotopes, and for an excitation temperature of 10 K, the inferred ^{13}CO column density is 7×10^{15} cm^{-2} and the total density is ~ 2000 cm^{-3}.

d) L1551

This source exhibits a bipolar ejection of material with velocities approaching 200 km s^{-1} (Snell, Loren, and Plambeck 1980). The ^{12}CO emission is optically thin, and its postshock column density is only 5×10^{15} cm^{-2} (an order of magnitude less than IC 443). The preshock density is estimated at $\sim 10^3$ cm^{-3}.

It is evident that the density and column density of the preshock gas in IC 443 are at least as high as in the other sources where HCO^+ enhancement does not exist. In spite of the various uncertainties, IC 443 definitely does not stand out as having the most rarefied preshock material. It therefore appears that the proposal by Mitchell and Deveau cannot explain the uniqueness of this source. In particular, for the preshock gas they used the chemical composition of the diffuse cloud toward ζ Per. However, the ^{12}CO column density of this source is only $\sim 5 \times 10^{14}$–10^{15} cm^{-2} (in contrast with a preshock CO column density of 5×10^{16} cm^{-2} for IC 443) and the total density a few 10^2 cm^{-3} (Snow 1977). It seems unlikely that its chemical composition bears a strong resemblance to that of IC 443.

The above discussion and the rich molecular structure of IC 443 (DeNoyer and Frerking 1981) suggest that the shock runs into a molecular region and that the unique HCO^+ enhancement stems from the particular conditions at this source.

IV. ENHANCED IONIZATION

It appears that the most plausible explanation for the HCO^+ enhancement in IC 443 is that the ionization rate in the shocked gas is higher than the standard cosmic ray value which led to the estimate of equation (2). What sets this source apart in the list of Rodriguez Kuiper and Dickinson is the fact that it is a young SNR. From X-ray observations, Malina, Lampton, and Bowyer (1976) deduce for it an age of only ~ 4000 yr. The analysis of Giovanelli and Haynes (1979) leads to an age estimate for the shell of IC 443 of

$$t \approx 3.3 \times 10^6/n \text{ yr} . \quad (6)$$

With the above mentioned estimates for the density n, the resulting age is in the range of ~ 3000–10,000 yr. In contrast, W44 is an old SNR whose age is probably a few 10^5 yr, at least (Cornett and Hardee 1975).

The cosmic rays produced in the supernova explosion may still be confined within the remnant boundaries of IC 443. It is well known that the cosmic ray interaction with the magnetic field leads to adiabatic losses and plasma instabilities which result in their confinement to the supernova cavity (e.g., Wentzel 1973; Kulsrud and Zweibel 1975). The shock front in IC 443 is almost certainly the boundary of the expanding supernova shell. The shocked material is therefore penetrating the SNR cavity where it is exposed to an enhanced rate of ionization, by the trapped cosmic rays, leading to the observed enhancement in HCO^+ abundance. Recent calculations by Morfill and Scholer (1979) show that cosmic ray confinement will persist, on the average, for $\sim 10^5$ yr after the explosion. This is consistent with the HCO^+ enhancement in IC 443 and with the lack of it in W44, in view of the age estimates for these two SNRs.

An alternative explanation for the enhanced ionization rate in the shocked material in IC 443 could conceivably be provided also by the presence of the nearby pulsar PSR 0611 + 22 since pulsars are probably also sources of cosmic rays. However, this would not explain why HCO^+ is enhanced across the shock front. In addition, the association between the SNR and the pulsar, which lies 0°6 outside the remnant, has been questioned by Malina *et al.* because the pulsar spin-down rate indicates an age of 90,000 yr (Graham and Hunt 1973).

Another possible explanation for a high ion abundance is ionization by the shock itself. The short distance covered by the shocked material during the recombination period eliminates this idea. A viable model must involve a high ionization rate sustained throughout the shocked region.

It thus appears that the most plausible explanation involves an increased ionization rate by the magnetically confined cosmic rays. An additional argument in favor of this model is provided by a problem with the molecular line widths. The emission from the shocked material is spanning a velocity range of ~ 50 km s^{-1}. Such large velocities are associated with shocks which lead to complete molecular dissociation. A similar problem exists with the shock in the Orion molecular cloud. It has been suggested that the Orion observations may be explained with high density knots being ejected from a central source (e.g., Chevalier 1980). However, such a model, and others, do not reproduce correctly the intensities and ratios of all the high excitation lines in Orion (Hollenbach 1982). The only model offered, so far, which can also reproduce the molecular line observations involves the inclusion of magnetic field effects which essentially soften the shock and lead to lower postshock temperatures (Hollenbach 1982; Draine, Roberge, and Dalgarno 1982). Likewise, the molecules in IC 443 may survive the impact of the shock, which is driven by the expanding shell at a velocity of ~ 50 km s^{-1}, because of the effect of the same magnetic field which is confining the cosmic rays. The shock compression n/n_0 can therefore be obtained via (e.g., Elitzur 1979*b*)

$$n/n_0 = 2^{1/2} V_S/V_A , \quad (7)$$

where V_S is the shock velocity and V_A is the Alfvén speed in the ambient gas. Assuming for the ambient field

$$B = 1 \mu G (n/\text{cm}^{-3})^{1/2} \quad (8)$$

(e.g., Draine *et al.*), the Alfvén speed is 1.85 km s^{-1}, and the shock compression is ~ 40. The density of the shocked material is therefore a few 10^4 cm^{-3}. This estimate is in agreement with the results of recent observations which failed to detect the $J = 3 \rightarrow 2$ transition of HCO^+ in the shocked gas (Plambeck 1982). The lack of a detectable $3 \rightarrow 2$ signal, in spite of the strong $1 \rightarrow 0$ emission, implies that the density is probably less than 10^5 cm^{-3}. Thus, the compression across the shock front is much smaller than expected for a 50 km s^{-1} shock, but in agreement with the softened compression of a magnetic shock.

From equation (2) the standard relative ionization in the postshock region would therefore be of order 10^{-7}, and the ion abundance $\sim 10^{-3}$ cm^{-3}. The HCO^+ enhancement therefore requires an ion density of $\sim 10^{-2}$–10^{-1} cm^{-3}. These values should be smaller than the electron abundance in the hot regions inside the SNR cavity. Indeed, an electron density of ~ 1.5 cm^{-3} is inferred for the very hot atomic region from [Fe x] data by Woodgate, Lucke, and Socker (1979).

V. DISCUSSION

The main conclusion of the discussion here is that shock enhancement of HCO^+ is the result of an increased ionization rate rather than any particular endothermic reaction. The problem is therefore one of astronomy rather than chemistry.

Shock enhancement of HCO^+ has apparently been detected in another SNR. Wootten (1981) has observed W28 in CO, HCO^+, and H_2CO. The preshock gas density, as estimated from ^{13}CO observations, is $\sim 2 \times 10^3$ cm^{-3}. In the direction which shows HCO^+ enhancement the preshock density is $\sim 2 \times 10^4$ cm^{-3}, and the density in the shocked region is $\sim 5 \times 10^5$ cm^{-3}. This estimate appears reliable because two of the HCO^+ lines were detected. The observations lead Wootten to conclude that "the enhanced HCO^+ emission in the line wings in the W28 active region indicates an enhanced HCO^+ abundance which can be directly traced to enhanced levels of ionizing radiation, such as cosmic rays, penetrating the cloud."

The observations of W28 provide strong support for the present model. Recent estimates show that the HCO^+/CO ratio in W28 is as high as in IC 443 (H. A. Wootten, private communication). The preshock density in the direction of maximum HCO^+ abundance is so high that the model of Mitchell and Deveau is clearly ruled out. The relatively modest density enhancement (about factor 20) across the W28 shock front is in agreement with the estimates of the previous section which take into account the softening effect of the magnetic field (the shock velocity in W28 is smaller than in IC 443). The age estimate for this SNR is less than 6×10^4 yr (Lozinskaya 1974). Hence, it is presumably still in its cosmic ray confinement phase.

The three SNRs associated with molecular clouds (W28, W44, and IC 443) are running into clouds with very similar properties. The only one among them not exhibiting HCO^+ enhancement is W44. This is in agreement with the model because it is also the only one among the three with age above the average cosmic ray confinement period.

Another source where an enhancement in the abundance ratio HCO^+/CO was reported is Orion (Kuiper, Rodriguez Kuiper, and Zuckerman 1980). The enhancement was found in a position north of the BN object. In view of the above, this enhancement is probing a region of a relatively high electron abundance. At this stage it would be hard to speculate about the origin of this ionization enhancement. The detailed mapping by Welch *et al.* (1981) shows that the HCO^+ emission in Orion is rather noisy and the extent of its enhancement is not yet clear. When the observational situation clears up, it should be possible to incorporate the result into a unified picture of Orion.

The enhanced ionization in the shocked material may affect the abundance of ions other than HCO^+. The only other ion observed toward IC 443 was N_2H^+ (DeNoyer and Frerking 1981), which was not detected. The upper limit on its column density was not significant when compared with the expected abundance in clouds, according to DeNoyer and Frerking.

It is not clear what the expected N_2H^+ abundance in the shocked region of IC 443 should be. Watson (1976) lists a number of differences between the chemistries of HCO^+ and N_2H^+ which indicate that the latter is not expected to follow the ionization rate in a straightforward manner like the former. In addition to the processes listed by Watson, an important destruction mechanism for N_2H^+, but not HCO^+, is interaction with O atoms which, as most models indicate, are highly abundant in molecular regions. The calculations of Iglesias and Silk (1978) show indeed that the N_2H^+ abundance in the shocked gas in their model is decreasing similarly to HCO^+ but at a smaller rate. Mitchell (1978) presents some calculations which do not cover ionization rates larger than the standard cosmic ray value (10^{-17} s^{-1}). His results do display a strong dependence of the HCO^+/N_2H^+ ratio on various depletion parameters. Prassad and Huntress point out that, unlike HCO^+, the N_2H^+ chemistry is temperature dependent, as evident also from their numerical results. An estimate of the expected N_2H^+ abundance in IC 443 would thus involve a full-scale calculation; it seems doubtful that a simple analogy with HCO^+ is appropriate.

Is there a conflict with the observations if N_2H^+ were to be enhanced as much as HCO^+ in IC 443? The theoretical studies mentioned above indicate that for solar abundance, standard cosmic ray ionization rate, and $T = 50$ K, the expected N_2H^+/HCO^+ abundance ratio is $\sim 1/10$–$1/20$ at the relevant densities. Lower temperatures or certain depletion patterns will reduce this ratio significantly. The observations of DeNoyer and Frerking yield an upper limit of $\sim 1/60$ toward IC 443, provided the excitation temperatures of the two species are the same. However, if $T_x(HCO^+) = 20$ K, while $T_x(N_2H^+) = 5$ K, for instance, then the observed limit is only 1/23, in agreement with the calculations mentioned above. Such a situation is quite likely because of the much smaller optical depth of N_2H^+. Indeed, large differences in optical depths were invoked by Turner and Thaddeus (1977) to explain the different spatial intensity distributions of N_2H^+ and HCO^+ in the sources they observed.

It is evident that the question of N_2H^+ abundance toward IC 443 requires further studies, observational as well as theoretical, before a meaningful comparison with the model can be made.

Discussion with L. K. DeNoyer, R. L. Plambeck, W. J. Welch, and H. A. Wootten are gratefully acknowledged. In particular, I would like to thank L. K. DeNoyer, R. L. Plambeck, and H. A. Wootten for their permission to quote results prior to publication. This work was supported in part by NSF grant AST 80-23712.

REFERENCES

Chevalier, R. 1980, *Ap. Letters*, **21**, 57.
Cornett, R. H., Chin, G., and Knapp, G. R. 1977, *Astr. Ap.*, **54**, 889.
Cornett, R. H., and Hardee, P. E. 1975, *Astr. Ap.*, **38**, 157.
DeNoyer, L. K., and Frerking, M. A. 1981, *Ap. J.* (*Letters*), **246**, L37.
Dickinson, D. F., Rodriguez Kuiper, E. N. Dinger, A. S. C., and Kuiper, T. B. H. 1980, *Ap. J.* (*Letters*), **237**, L43.
Draine, B. T., Roberge, W. G., and Dalgarno, A. 1982, preprint.
Elitzur, M. 1979*a*, *Ap. J.*, **229**, 560.
———. 1979*b*, *Astr. Ap.*, **73**, 322.
Elitzur, M., and Watson, W. D. 1978, *Ap. J.* (*Letters*), **222**, L141.
Elmegreen, B. G., and Lada, C. G. 1978, *Ap. J.*, **219**, 467.
Giovanelli, R., and Haynes, M. P. 1979, *Ap. J.*, **230**, 404.
Graham, D., and Hunt, G. 1973, *Nature Phys. Sci.*, **242**, 86.
Hartquist, T. W., Oppenheimer, M., and Dalgarno, A. 1980, *Ap. J.*, **236**, 182.
Herbst, E., and Klemperer, W. 1973, *Ap. J.*, **185**, 505.
Hollenbach, D. 1982, *Ann. NY Acad. Sci.*, in press.
Iglesias, E., and Silk, J. 1978, *Ap. J.*, **226**, 851.
Knapp, G. R., and Kerr, F. J. 1974, *Astr. Ap.*, **33**, 463.
Kuiper, T. B. H., Rodriguez Kuiper, E. N., and Zuckerman, B. 1980, in *Interstellar Molecules*, ed. B. H. Andrew (Dordrecht: Reidel), p. 31.
Kulsrud, R., and Zweibel, E. 1975, *14th Internat. Cosmic Ray Conf.*, 465.
Lada, C. J., and Harvey, P. M. 1981, *Ap. J.*, **245**, 58.
Lozinskaya, T. A. 1974, *Soviet Astr.—AJ*, **17**, 603.
Malina, R., Lampton, M., and Bowyer, S. 1976, *Ap. J.*, **207**, 894.
Mitchell, G. F. 1978, *A.J.*, **83**, 1612.
Mitchell, G. F., and Deveau, T. J. 1982, preprint.
Mitchell, G. F., Ginsburg, J. L., and Kuntz, P. J. 1978, *Ap. J. Suppl.*, **38**, 39.
Morfill, G. E., and Scholer, M. 1979, *Ap. J.*, **232**, 473.
Plambeck, R. L. 1982, private communication.
Prassad, S. S., and Huntress, W. T. 1980, *Ap. J. Suppl.*, **43**, 1.
Rodriguez Kuiper, E. N., and Dickinson, D. F. 1980, *Bull. AAS*, **12**, 865.
Scoville, N. Z., Irvine, W. M., Wannier, P. G., and Predmore, C. R. 1977, *Ap. J.*, **216**, 320.
Snell, R. L., Loren, R. B., and Plambeck, R. L. 1980, *Ap. J.* (*Letters*), **239**, L17.
Snow, T. P. 1977, *Ap. J.*, **216**, 724.
Turner, B. E., and Thaddeus, P. 1977, *Ap. J.*, **211**, 755.
Watson, W. D. 1976, *Rev. Mod. Phys.*, **48**, 513.
Welch, W. J., Wright, M. C. H., Plambeck, R. L., Bieging, J. H., and Baud, B. 1981, *Ap. J.* (*Letters*), **245**, L87.
Wentzel, D. G. 1973, *Ap. Space Sci.*, **23**, 417.
Woodgate, B. E., Lucke, R. L., and Socker, D. G. 1979, *Ap. J.* (*Letters*), **229**, L119.
Wootten, H. A. 1977, *Ap. J.*, **216**, 440.
———. 1981, *Ap. J.*, **245**, 105.

MOSHE ELITZUR: Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506