NASA-CR-200301

IN-90

P. 10

ASTRONOMICAL SOCIETY OF THE PACIFIC
CONFERENCE SERIES

Volume 80

THE PHYSICS OF THE INTERSTELLAR MEDIUM AND INTERGALACTIC MEDIUM

A Meeting in Honor of Professor George B. Field

EIPC, Marciana Marina, Isola d'Elba, Italy
20-24 June 1994

Edited by
A. Ferrara, C. F. McKee, C. Heiles,
and P. R. Shapiro

A SERIES OF BOOKS ON RECENT DEVELOPMENTS IN ASTRONOMY AND ASTROPHYSICS

Printed by BookCrafters, Inc.

First published 1995

Library of Congress Catalog Card Number: 95-76618
ISBN 0-937707-99-6

D. Harold McNamara, Managing Editor of Conference Series
408 ESC Brigham Young University
Provo, UT 84602
801-378-2298

The Physics of the Interstellar Medium and Intergalactic Medium
ASP Conference Series, Vol. 80, 1995
A. Ferrara, C.F. McKee, C. Heiles, and P.R. Shapiro (eds.)

COSMIC-RAY HEATING OF THE INTERSTELLAR GAS

MITCHELL C. BEGELMAN[1]
Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, CO 80309-0440

ABSTRACT Cosmic rays streaming out of the Galaxy can become locked to resonantly excited Alfvén waves as they pass through a region of increasing temperature at the disk-halo interface. A large fraction of the energy in $\gtrsim 1$ GeV cosmic rays goes into heating of the thermal gas via nonlinear Landau damping of the waves. This mode of cosmic-ray heating can balance radiative cooling for gas in the temperature range $10^{4.5}$ K $\lesssim T \lesssim 10^6$ K, creating a thermal transition zone with a column density exceeding that of an ordinary conductive interface. This layer could be the site of much of the observed emission and absorption by highly ionized species such as C IV, N V, and O VI.

INTRODUCTION

The dominant legacy of the famous paper by Field, Goldsmith, and Habing (1969; hereafter FGH) is the idea of multiphase thermal equilibria in the interstellar medium (ISM) and elsewhere. But we should not forget that the title of the paper (which I have appropriated for my talk) emphasizes another important theme, the possible role of cosmic rays in heating the ISM. As we have heard at this meeting (from McKee and others), the original heating mechanism for H I proposed by FGH — inelastic collisions of H atoms with ~2 MeV cosmic rays — appears to be relatively unimportant compared, for example, to photoelectric heating of grains. But given George Field's farsightedness in so many areas of contemporary astrophysics, it would be foolhardy to dismiss the idea of cosmic ray heating of the ISM altogether. I will argue in this talk that cosmic-ray heating may be important after all, albeit in a rather different way than was envisaged by FGH.

There is certainly enough energy available in cosmic rays to affect the thermal balance of the ISM. The cosmic-ray pressure is estimated to be comparable to that of the gas, $P_{\rm CR} \approx 6 \times 10^{13}$ ergs cm^{-3}, with the energy content dominated by $\sim$ GeV protons. Their inferred lifetimes are consistent with escape from the Galaxy at a mean speed $\lesssim 100$ km s^{-1}, implying a cosmic-ray energy flux $\sim 3 \times 10^{40}$ ergs s^{-1} integrated over the Galactic disk. While this is probably no more than about 10% of the energy supply needed to power the entire ISM,

[1]Also at Department of Astrophysical, Planetary, and Atmospheric Sciences, University of Colorado, Boulder, CO 80309-0391.

it could dominate the thermal structure locally if efficient heating occurred only as the cosmic rays passed through certain regions. As I will argue below, this is exactly what we expect to happen. The fact that the cosmic-ray particles do not stream freely out of the Galaxy at speeds $\sim c$, but rather "drift" at a much lower mean speed, indicates that the particles are well-coupled to the gas, most likely via Alfvén waves excited by the cosmic rays themselves. I will argue that the coupling occurs mainly at the last interface between cool ($T \lesssim 3 \times 10^4$ K) and hot gas as the cosmic rays stream into the Galactic halo. Intense heating of the gas, by Alfvén wave damping, occurs mainly in this layer, using up a substantial fraction of the cosmic-ray energy flux.

THEORY OF COSMIC-RAY TRANSPORT

At about the same time as George and his collaborators were worrying about the neutral phases of the ISM, several groups were developing an elegant theory for cosmic-ray transport which proves to be most applicable in the ionized phases (Lerche 1967; Kulsrud and Pearce 1969; Wentzel 1969; Skilling 1971). The qualitative results of the theory are as follows. If the sources of cosmic rays are concentrated towards the disk of the Galaxy, there will be a net gradient of cosmic-ray density between the disk and the halo. This will cause the cosmic rays to "drift" along magnetic field lines that lead out of the Galaxy, which really means that the momentum distribution function of cosmic ray particles has a small anisotropy. If this anisotropy exceeds a certain threshold, which depends on the ionization state of the local ISM, plasma instabilities will excite Alfvén waves, which scatter the cosmic rays and thus try to limit the level of anisotropy *in the frame comoving with the mean phase speed of the waves.* This has the effect of limiting the cosmic-ray drift speed. Moreover, the continuous excitation and damping of Alfvén waves channels energy from the cosmic ray particles into the background gas, thus heating the ISM (Wentzel 1974). The tricky part of the theory is that the coupling between cosmic rays and waves can be far from perfect, resulting in diffusion relative to the waves. There has been considerable debate over the importance of diffusion compared to convection at the wave speed (e.g., Kulsrud and Cesarsky 1971), and the issue is not yet settled. Where diffusion dominates the transport, the cosmic-ray pressure gradient can be suppressed, and with it the heating.

There have been only a few efforts to apply the full cosmic-ray transport theory to the structure of the ISM, including effects of both convection and diffusion. Most of these have focused on such aspects as pressure support by cosmic rays (Hartquist and Morfill 1986; Siemieniec and Cesarsky 1991) and cosmic-ray driven winds (Breitschwerdt, McKenzie, and Völk 1991, 1993), or the diffusion of synchrotron-emitting electrons into the halo (Siemieniec and Cesarsky 1991). Related applications have been made to systems such as cooling flows in clusters of galaxies (Böhringer and Morfill 1988; Loewenstein, Zweibel, and Begelman 1991). I will focus primarily on the *thermal* effects of cosmic-ray transport, i.e., heating by the damped waves.

Where the scattering is sufficiently rapid, the cosmic ray distribution will be nearly isotropic in the wave frame. The "convection–diffusion" equation is derived by expanding the full Vlasov equation in inverse powers of the scattering frequency, and averaging over pitch angles (Skilling 1971, 1975; Blandford and Eichler 1987). This equation can be written in the form

$$\frac{\partial f}{\partial t} + \mathbf{v}_A \cdot \nabla f = \frac{1}{3}(\nabla \cdot \mathbf{v}_A) p \frac{\partial f}{\partial p} + \nabla \cdot \left(D \nabla_{\|} f \right) \tag{1}$$

for the simple case of transport through a stationary medium, where $f(p)$ is the isotropic part of the momentum distribution function, v_A is the mean speed of the resonant waves, $\nabla_{\|} f$ is the cosmic-ray gradient parallel to the magnetic field, and D is a spatial diffusion coefficient. If the only waves capable of scattering the cosmic rays (i.e., resonant with the gyrofrequency in the guiding center frame: see Blandford and Eichler 1987) are excited by the streaming cosmic rays themselves, as we shall assume throughout, then v_A is simply the local Alfvén speed and the waves propagate down the cosmic-ray gradient. Skilling (1975) treats the more complicated situation in which there are additional sources of waves, in which case v_A is smaller and there must be an additional term to describe diffusion in momentum space, i.e., second-order Fermi acceleration.

The physical interpretation of equation (1) is straightforward. The terms on the left-hand side describe the advection of cosmic rays at the local wave speed; the first term on the right-hand side represents adiabatic energy gains and losses due to changes in the advection speed, i.e., first-order Fermi acceleration on the scattering centers; and the second term on the right-hand side describes spatial diffusion, i.e., slippage relative to the wave frame. The mean cosmic-ray "drift" speed (i.e., the speed of the frame in which the cosmic-ray flux vanishes) is given by

$$v_d = \frac{1}{f(p)} \left[-\frac{1}{3} v_A p \frac{\partial f}{\partial p} - D \nabla_{\|} f \right] \tag{2}$$

(Blandford and Eichler 1987). When diffusion is negligible, the cosmic rays can be said to be "locked" to the wave frame and the drift speed will be of order the Alfvén speed, although not exactly equal to v_A because of the derivative with respect to momentum (Wentzel 1974). For the cosmic rays in the Galaxy, which have $f(p) \propto p^{-4.5}$, the convection speed would be $1.5 v_A$.

Two additional conditions must be satisfied in order for equation (1) to describe the propagation of cosmic rays of a given momentum p. First, the drift speed v_d must exceed a certain critical speed v_{crit}, which represents the threshold for triggering Alfvén wave growth. Second, $\mathbf{v}_A \cdot \nabla f$ must be negative, which is the self-consistency condition to ensure that the cosmic rays transfer energy to the waves and not the other way around. Where these conditions are not satisfied, the cosmic rays are not coupled to the background gas through Alfvén wave scattering and $\nabla_{\|} f$ vanishes.

COSMIC-RAY DIFFUSION COEFFICIENT

If the waves are all generated by streaming instabilities, then the diffusion coefficient in equation (1) can be calculated self-consistently in terms of the gradient of the distribution function. The effective scattering frequency ν is related to

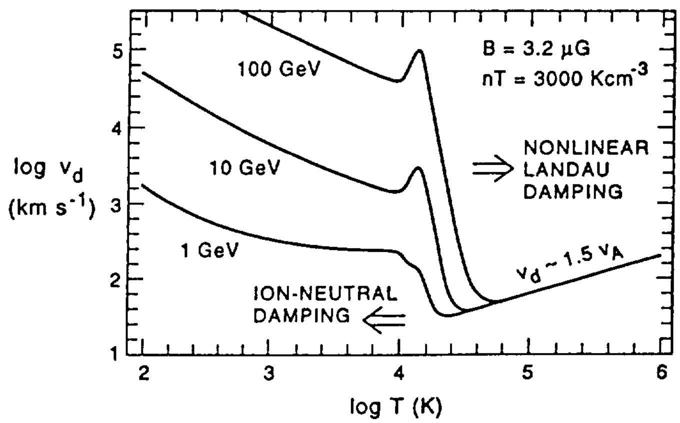

FIGURE I Critical drift speed for triggering growth of Alfvén waves as a function of background temperature, for cosmic-ray protons of energy 1, 10, 100 GeV, with energy distribution $n(>\varepsilon) = 2\times10^{-10}(\varepsilon/1\ \mathrm{GeV})^{-1.5}\ \mathrm{cm}^{-3}$. Other details of calculation are described in text.

the fractional wave amplitude $(\delta B/B)$ through

$$\nu \approx \frac{\pi}{2}\left(\frac{\delta B}{B}\right)^2 \Omega_L, \tag{3}$$

where $\Omega_L = eB/p$ is the cosmic-ray Larmor frequency. The wave amplitude is determined by a local balance between the growth rate due to instability and the damping rate, Γ. One can express the effective scattering rate by

$$\nu = -\frac{2\pi^3 ec}{\Gamma B}|\mu|\int_{|\mu|p}^{\infty} dp'[(p')^2 - |\mu|^2p^2]\mathrm{v}_A\cdot\nabla f(p') \tag{4}$$

(Skilling 1971), where μ is the cosine of the pitch angle. In weakly ionized regions, damping occurs mainly through ion–neutral collisions, with a rate given by

$$\Gamma_{in} \approx 1.6\times10^{-9}(1-x)n\left(\frac{T}{100\ \mathrm{K}}\right)^{0.37}\ \mathrm{s}^{-1} \tag{5}$$

for 100 K $< T <$ 10^4 K, where n is the total H density and x is the ionization fraction (Kulsrud and Pearce 1969; Zweibel and Shull 1982). For linear damping mechanisms such as ion–neutral damping, the critical drift speed for triggering the instability can be considerably larger than v_A, as shown in Fig. I. To calculate these curves we assumed fixed $B = 3.2\ \mu$G and $p/k = 3000$ K cm^{-3}, so that the $v_A = x^{-1/2}v_i$, where v_i is the ion thermal speed. The ionization level is determined by the combination of charge exchange with C II (giving $x_C = 5\times10^{-4}$), ionization by low-energy cosmic rays with $\zeta_{\mathrm{CR}} = 7\times10^{-18}\ \mathrm{s}^{-1}$ (Spitzer 1978), and coronal ionization equilibrium. At temperatures exceeding about 3×10^4 K, the ionization level is so high that ion–neutral damping is negligible and the critical drift speed (for $f(p)\propto p^{-4.5}$) approaches $1.5v_A$. In these regions there is no effective *linear* damping mechanism, and the dominant damping mechanism is probably nonlinear Landau damping (Lee and Völk 1973; Cesarsky and Kulsrud 1981), with a rate given by

$$\Gamma_{nl} \approx \left(\frac{\pi}{8}\right)^{1/2} \left(\frac{v_i}{c}\right) \left(\frac{\delta B}{B}\right)^2 \Omega_L \times \min\left[1, \left(\frac{v_i}{c}\right) \left(\frac{\delta B}{B}\right)^{-1}\right]. \tag{6}$$

The second term inside the square bracket represents the saturation of the damping rate due to ion trapping (Völk and Cesarsky 1982).

The diffusion coefficient is determined from the collision frequency by

$$D = c^2 \left\langle \frac{1-\mu^2}{2\nu} \right\rangle, \tag{7}$$

where the angle-bracket denotes an average over pitch angle. The nonlinearity is immediately obvious. For the case of ion–neutral damping, $D \propto |\nabla_{||} f|^{-1}$ implying that the diffusion term in equation (1) is independent of the cosmic ray gradient, as Skilling (1971) pointed out. For the case of nonlinear damping the dependence is more subtle since the damping coefficient (6) is related to ν through both equations (3) and (4), implying $D \propto |\nabla_{||} f|^{-1/2}$ and $D \propto |\nabla_{||} f|^{-2/3}$ for unsaturated and saturated nonlinear Landau damping, respectively. The effects of linear vs. nonlinear damping on the evolution of $f(p)$ are completely different. In the limit of large linear damping, the diffusion term balances the advection terms in equation (1), and the adiabatic losses are relatively unimportant. This can lead to large modifications in the cosmic-ray distribution function over short distances compared to the scale length for changes in v_A. When wave growth is limited by nonlinear damping, however, it is the adiabatic term that balances the diffusion term in the limit of large damping, with the result that the drift never exceeds v_A by a large factor and the magnitude of $\nabla_{||} f$ is suppressed.

APPLICATION TO THE ISM

A Simple Model Problem

Let us now study an extremely simple model for cosmic ray propagation in the ISM, in order to illustrate some possible consequences of the effects discussed above. We assume a one-dimensional model in which the magnetic field strength is constant along a field line, but the gas temperature and density may vary with position. Cosmic rays are probably produced in disturbed regions of the ISM, e.g., supernova remnants and stellar wind bubbles, in which the gas temperature is rather high ($\sim 10^6$ K). A high temperature is likely encountered again in the halo, but what of the region in between? To make the problem interesting, let us assume that the cosmic rays must cross an H I cloud in order to leave the Galaxy. The temperature and critical drift speed as a function of position along the path of cosmic-ray flow are shown schematically in Fig. II.

To characterize cosmic-ray transport from one side of the cloud to the other, we must first determine *where* equation (1) is applicable, i.e., where the drift speed exceeds the critical speed. Conditions for coupling via Alfvén waves clearly apply beyond the last minimum encountered by the cosmic rays on the v_{crit}

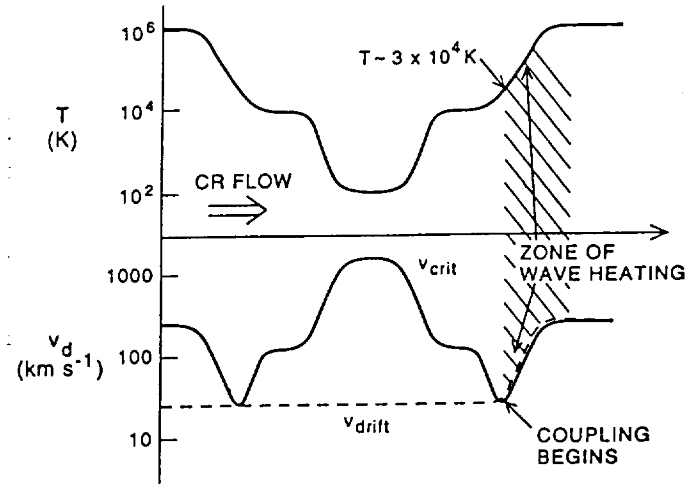

FIGURE II Schematic illustration of cosmic ray flow (left-to-right) from a hot region in the disk to the hot halo, via an H I cloud. Cosmic rays are not trapped by resonantly excited Alfvén waves until they reach the *second* minimum of v_{crit}, which occurs at $T \approx 3 \times 10^4$ K on the downstream side of the cloud. Intense wave heating of the ISM occurs beyond this point.

curve. In this one-dimensional case with v_{crit} solely a function of temperature, this is the only region in which the conditions for wave coupling are satisfied, and we have labeled this the "zone of wave heating." The reason is that this last minimum forms a bottleneck for cosmic-ray flow through the entire system. It is difficult to arrange for v_d to decrease in a wave zone without having $\mathbf{v}_A \cdot \nabla f > 0$, which violates a condition for coupling. Thus, the fact that the cosmic rays must pass the second minimum in the v_{crit} curve restricts the drift speed upstream of the minimum, such that waves are not excited anywhere in this region.

Since the zone of wave heating only includes ISM at $T \gtrsim 3 \times 10^4$ K we can neglect ion–neutral damping, and solve the convection–diffusion equation using the diffusion coefficient for nonlinear Landau damping. A quantitative analysis indicates that the damping will be saturated at all temperatures. This is important for the heating of the ISM because saturation suppresses the damping rate, leading to larger waves amplitudes and more effective coupling of cosmic rays to waves. The relative importance of convection and diffusion depends on the scale length of the temperature transition layer. For our assumed ISM parameters one can show that diffusion dominates only where the thermal gradient scale is smaller than $5 \times 10^{15} \tilde{T}(\tilde{T}^{1/2} - 1)^{-3}$ cm where $\tilde{T} \equiv T/3 \times 10^4$ K, i.e., very small indeed. This result implies that cosmic-ray diffusion is *not* important through most of the transition layer.

Heating of the ISM

Once we have determined ∇f from the convection–diffusion equation, the cosmic-ray pressure gradient is readily calculated as $\nabla P_{\rm CR} \approx 4\pi c \int (\nabla f) p^3 dp$ (for relativistic cosmic ray particles). The volume heating rate is then given by

$$\mathcal{H}_{\rm CR} = -\mathbf{v}_A \cdot \nabla P_{\rm CR}. \tag{8}$$

The thermal length scale of the transition layer may be affected by many factors, including thermal conduction, mixing effects, and pressure gradients. However, let us consider the simplest possible case in which radiative cooling of the gas is completely balanced by $\mathcal{H}_{\rm CR}$. Since the cosmic rays are forced to advect at a speed proportional to the Alfvén speed, the cosmic-ray pressure responds adiabatically to changes in v_A. For a fully relativistic cosmic-ray distribution with $f(p) \propto p^{-4.5}$ (and a lower cutoff energy), this corresponds to a cosmic ray "equation of state" $P_{\rm CR} \propto v_A^{-3/2} \propto n^{3/4}$. (Note that a self-consistent treatment of the mildly relativistic regime would modify this result.)

If the cooling rate per unit volume is $n^2\Lambda(T)$ and we impose the condition of hydrostatic equilibrium $P_{\rm CR} + P_{\rm gas}$ = const., then it is possible to solve for the structure of the thermal transition layer. At $T \gg 3 \times 10^4$ K, $P_{\rm CR} \propto T^{-3/4}$ and the distribution of gas column densities with temperature is given by

$$\frac{dN_H}{d\ln T} \approx 2 \times 10^{17} \Lambda_{22}^{-1} \left(\frac{T}{3 \times 10^4 \text{ K}}\right)^{3/4} \text{ cm}^{-2}, \tag{9}$$

where $\Lambda_{22} \equiv \Lambda/10^{-22}$ cm^3 s^{-1} represents the typical order of magnitude of the cooling function at temperatures between $10^{4.5}$ and 10^6 K (Spitzer 1978). Thermal conduction at the Spitzer rate (Spitzer 1962), which is often invoked to set the length scale for thermal transition layers at these temperatures, is unimportant in such a broad layer, for $T < 10^6 \Lambda_{22}^{-1}$ K.

CONCLUSIONS

My message is that cosmic rays may play an important role in heating certain parts of the ISM, after all. The heating mechanism that can do the job is the damping of Alfvén waves which have been driven unstable by streaming cosmic rays. In other words, the heating rate depends on the global flow of cosmic rays, not on its local properties as in the FGH model for H I clouds. Unfortunately, this makes it much more difficult to calculate a model in detail, since the heating would be sensitive to boundary conditions and the magnetic and phase topology of the ISM, i.e., such issues as whether the cosmic rays stream through cool clouds on their way out of the Galaxy, or tend to avoid them. The state of motion of the ISM and additional sources of resonant Alfvén waves, both of which I have ignored in my simple model, are two additional effects that must be considered.

Nevertheless, the effect has some attractive features which make it worthy of further study. Most of the heating would occur as the cosmic rays pass through the *last* region of cool gas they traverse on their way into the halo. Since the cosmic rays are well-coupled to the waves in this region, the heating is potentially very efficient: those cosmic ray protons that are coupled to waves would lose more than 20% of their energy in every thermal e-folding length. Moreover, the mechanism would heat a segment of the ISM for which convincing heating mechanisms have proven notoriously elusive: the regions at high Galactic latitude with $10^{4.5}$ K $\lesssim T \lesssim 10^6$ K, which are responsible for the observed absorption and emission by highly ionized species such as C IV, N V, and O VI. Given the observed energy density in cosmic rays, this mechanism could supply enough heat to account for much of the column density inferred to exist in these species (Shull and Slavin 1994; Martin and Bowyer 1990).

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation (grant AST91-20599) and the National Aeronautics and Space Administration (grant NAGW-766). I am grateful to E. Zweibel and M. Shull for enlightening discussions, and to C. Cesarsky for alerting me to her recent work in this area.

REFERENCES

Blandford, R. D., and Eichler, D. 1987, *PhysRep*, **154**, 1

Böhringer, H., and Morfill, G. E. 1988, *ApJ*, **330**, 609

Breitschwerdt, D., McKenzie, J. F., and Völk, H. J. 1991, *A&A*, **245**, 79

Breitschwerdt, D., McKenzie, J. F., and Völk, H. J. 1993, *A&A*, **269**, 54

Cesarsky, C. J., and Kulsrud, R. M. 1981, in *Origin of Cosmic Rays, IAU Symp. 94*, G. Setti, G. Spada, and A. W. Wolfendale, Dordrecht: Reidel, 251

Field, G. B., Goldsmith, D. W., and Habing, H. J. 1969, *ApJ*, **155**, L149 (FGH)

Hartquist, T. W., and Morfill, G. E. 1986, *ApJ*, **311**, 518

Kulsrud, R. M., and Pearce, W. P. 1969, *ApJ*, **156**, 445

Kulsrud, R. M., and Cesarsky, C. J. 1971, *ApLett*, **8**, 189

Lee, M. A., and Völk, H. J. 1973, *Ap&SS*, **24**, 31

Lerche, I. 1967, *ApJ*, **147**, 689

Loewenstein, M., Zweibel, E. G., and Begelman, M. C. 1991, *ApJ*, **377**, 392

Martin, C., and Bowyer, S. 1990, *ApJ*, **350**, 242

Shull, J. M., and Slavin, J. D. 1994, *ApJ*, **427**, 784

Siemieniec, G., and Cesarsky, C. 1991, *A&A*, **245**, 418

Skilling, J. 1971 , *ApJ*, **170**, 265

Skilling, J. 1975, *MNRAS*, **172**, 557

Spitzer, L. 1962, *Physics of Fully Ionized Gases*, 2d ed., New York: Wiley

Spitzer, L. 1978, *Physical Processes in the Interstellar Medium*, New York: Wiley

Völk, H. J., and Cesarsky, C. J. 1982, *Z. Naturforsch.*, **37a**, 809

Wentzel, D. G. 1969, *ApJ*, **157**, 545

Wentzel, D. G. 1974, *ARA&A*, 12, 71

Zweibel, E. G., and Shull, J. M. 1982, *ApJ*, **259**, 859