The generation of low-energy cosmic rays in molecular clouds *

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Abstract

It is argued that if cosmic rays penetrate into molecular clouds, the total energy they lose can exceed the energy from galactic supernovae shocks. It is shown that most likely galactic cosmic rays interacting with the surface layers of molecular clouds are efficiently reflected and do not penetrate into the cloud interior. Low-energy cosmic rays ($E < 1 \text{ GeV}$) that provide the primary ionization of the molecular cloud gas can be generated inside such clouds by multiple shocks arising due to supersonic turbulence.

1 Introduction

Gas phase chemical reactions in molecular clouds are predominantly ion-molecular reactions, and are catalyzed by $H^+$, $H_2^+$, and $H_3^+$ ions, which are produced, in turn, by low-energy cosmic rays ($E \lesssim 1 \text{ GeV}$; see the review [1]). The primary ionization rate by cosmic rays required to sustain the fractional ionization and concentrations of these ions is estimated to be $\zeta \sim 10^{-17} \text{ s}^{-1}$. A similar value is obtained for the upper limit to the primary ionization rate derived from the abundances of HD in molecular clouds, $\zeta \lesssim 10^{-16} - 10^{-17} \text{ s}^{-1}$ [2, 3]. It was first proposed in [4] that the fractional ionization in the cores of molecular clouds might exceed the value corresponding to $\zeta \sim 10^{-17} \text{ s}^{-1}$ by a factor of five, which would require that $\zeta$ be increased by a factor of 25. Based on the assumption that the

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predominant magnetic field structure in molecular clouds is dipolar, it was shown in [5] that cosmic rays with energies $E > 1\text{ MeV/nucleon}$ essentially freely penetrate into their interior, with ionization losses constituting about 10% of their energy (see also [6]). For this reason, the above estimates of the primary ionization rate are considered to be valid for the interstellar medium as well. However, new data on the properties of molecular clouds and new theoretical analysis of their nature have recently cast doubts on the unconditionality of the conclusions of [5] and the general view that the primary ionization rates by cosmic rays in molecular clouds and in the ISM are in agreement. We present here arguments supporting the idea that cosmic rays with energies $E \lesssim 1\text{ GeV}$ are not able to penetrate into the interiors of molecular clouds, so that the presence of such particles there suggests that high-energy, nonrelativistic, nonthermal particles are generated within the molecular clouds themselves. This could occur, in particular, due to MHD shock waves arising in clouds during their formation from diffuse gas.

Section 2 presents estimates of the total energy lost by galactic cosmic rays in molecular clouds, and shows that these energy losses exceed the total energy rate injected by supernovae into cosmic rays. Section 3 presents arguments based on the results of recent numerical modeling that suggest that the magnetic field structure in molecular clouds should differ from a simple dipolar field, and probably has a toroidal (helical) component in the plane perpendicular to the rotational axis of the cloud. In this case, most of the cosmic rays incident on the cloud should be reflected. Section 4 presents estimates of the efficiency of the acceleration of cosmic rays by MHD shock waves in molecular clouds. Finally, Section 5 summarizes our conclusions.

2 Energy losses of cosmic rays in molecular clouds

It can easily be shown that the dominant contribution to the primary ionization rate by galactic cosmic rays with an energy spectrum [7]

$$J(E) \simeq \frac{3 \times 10^4}{(800 + E)^{2.5}} \text{ (cm}^2\text{ sr s MeV)}^{-1}, \ E < 10\text{ GeV}$$

(1)

is provided by cosmic rays with energies $E < 1\text{ GeV}$ (the energy $E$ in (1) is in MeV); the spectrum has a break at energies $E > 10\text{ GeV}$, where its slope becomes steeper. The fraction of the total energy $E = \gamma m_p c^2$ lost by a cosmic ray particle (proton) as it passes through material with a hydrogen density along the path $N_L$ is determined to order of magnitude as [6]
\[
\delta E = \frac{4\pi e^4 \Lambda}{m_e c^2 m_p c^2} \frac{\gamma}{\gamma^2 - 1} N_L \simeq (0.5 - 1) \times 10^{-4} \frac{\gamma}{\gamma^2 - 1} N_{L,22},
\]

where \( \Lambda = \ln[2m_e c^2 \beta^2 / I(1 - \beta^2)] - \beta^2 \simeq 5 - 12 \) for energies from 1 MeV to 1 GeV, \( N_{L,22} = 10^{-22} N_L \), \( \beta = v/c \), and \( c \) is the speed of light. As it penetrates into a cloud, a high-energy particle undergoes numerous scatterings, so that the total path length travelled by the particle in the cloud is \( L \sim 4cR^2/D \), where \( R \) is the radius of the cloud and \( D \) is the diffusion coefficient for cosmic rays in the cloud. The total density of particles along the trajectory is \( N_L \sim 2NR/\lambda \gg N \) [6], where \( \lambda \) is the characteristic correlation scale for turbulence in the magnetic field, \( \lambda \ll R \), and \( N \) is the surface density of the molecular cloud. Observed molecular clouds display a roughly constant (independent of radius) surface density of \( N = 1.5 \times 10^{22} \) cm\(^{-2} \) (see the review [8]). Thus,

\[
\delta E \sim (1.5 - 3) \times 10^{-4} \frac{\gamma}{\lambda_R (\gamma^2 - 1)},
\]

where \( \lambda_R = \lambda/R \); for \( E_k = 100 \) MeV and \( \lambda_R = 0.1 \), we find \( \delta E \sim 0.01 \).

The energy absorbed by all the molecular clouds in the Galaxy is

\[
\dot{E}_{MC}^c = S \int_{100 \text{ MeV}}^{\infty} \delta E EJ(E)dE \sim 4 \times 10^{-5} S \lambda_R^{-1} \text{ erg/s},
\]

where \( S \) is the total surface area of a molecular cloud. Adopting for the entire Galaxy the molecular cloud spectrum obtained in [9],

\[
\frac{dN}{dM} = AM^{-1.73},
\]

over the interval \( M = [M_1 = 10^2, M_2 = 10^6]M_\odot \) with the normalization factor \( A = 3.5 \times 10^7 \), we can find the total surface area of clouds

\[
S = 4\pi \int_{M_1}^{M_2} R^2 \frac{dN}{dM} dM = 7 \times 10^{46} \sigma n^{-2/3},
\]

where \( n \sim 10^2 \) cm\(^{-3} \) is the mean gas density in the clouds, and \( \sigma > 1 \) is a factor accounting the fact that the surface area of a cloud is greater than that of a sphere due to irregularities in the cloud boundary [10]. When calculating the normalization coefficient \( A \), we assumed that the mass spectrum of molecular clouds determined in [9] for the Perseus arm is valid for
the Galaxy as a whole, with the mass of molecular gas in the Galaxy being $5 \times 10^9 M_\odot$. This yields $S \simeq 3 \times 10^{45} \sigma \text{ cm}^2$, and $\dot{E}_{MC}^{cr} \simeq 2 \times 10^{42} \sigma / \lambda_R \text{ erg s}^{-1}$ for the energy losses of cosmic rays in clouds. The production of energy in galactic cosmic rays in supernovae is $\dot{E}_{SN}^{cr} \sim 10^{42} \eta \nu_1/30 \text{ erg s}^{-1}$, where $\eta < 1$ is the fraction of the supernova energy that goes into cosmic rays (for which modern estimates yield $\eta \sim 0.1$ [11]), and $\nu_1/30$ is the supernova rate in the Galaxy in units of explosions per 30 years. It can readily be verified that, for $\eta \sim 0.1$ and $\lambda_R \sim 0.1$, the amount of energy in cosmic rays that is absorbed by molecular clouds is higher than the amount of cosmic-ray energy produced in supernovae. In fact, this conclusion can be stated more firmly: with the adopted assumptions, $\dot{E}_{SN}^{cr} \ll \dot{E}_{MC}^{cr}$, which implies that probably $\lambda_R \ll 0.1$. Indeed, if in reality the correlation length is determined by viscosity, then $\lambda_R \sim (\ell/R)^{3/4}$, where $\ell$ is the mean free path of the particles ($\ell \ll R$) [6]. Recent numerical modeling of MHD turbulence in molecular clouds [12, 13] suggests that the correlation length is 0.01-0.03 of the scale on which energy is injected into the system, which in our case is the radius of the cloud. To resolve this inconsistency between the cosmic ray energy that could be absorbed in molecular clouds and the cosmic ray energy produced by supernovae, we must suppose that galactic cosmic rays interacting with molecular clouds are predominantly reflected, so that only a small fraction of the cosmic ray energy is lost.

3 Reflection of cosmic rays from the surface layers of molecular clouds

According to recent numerical modeling, molecular clouds represent transient regions of enhanced density arising due to the action of converging flows of interstellar gas [14–17], whose lifetimes, $t_{MC} \sim 2 \times 10^7 - 10^8 \text{ yr}$, are probably determined by the activity of the stars born in them. In this picture, one of the main sources of turbulent energy in molecular clouds is the kinetic energy of the converging flows, although it is not ruled out that an appreciable amount of energy can be contributed by young stars born in the molecular cloud cores. During the formation of a molecular cloud – i.e., the transformation of atomic into molecular hydrogen in the process gas compression – some fraction of its rotational angular momentum is lost, but the remaining specific angular momentum of the cloud is still substantial: on average, the specific angular momentum in molecular clouds is a factor of four lower than the specific angular momentum of the diffuse interstellar
gas. This means that on the lifetime a cloud rotates about 30 times as it is compressed in the converging flows (we have adopted here a characteristic rotational velocity for the cloud $\Omega \sim 10^{-14}$ s$^{-1}$ [18]). Thus, we expect the magnetic field in the outer parts of the molecular cloud to have a helical structure with an appreciable toroidal component (i.e., the component perpendicular to the rotational axis of the cloud). This type of field structure is indeed observed in a number of cases (such as the cloud Lynds 1641) [19]. In this case, no matter what the angle at which a cosmic ray particle is incident on the molecular cloud surface, the pitch angle will reach its critical value as the particle penetrates into the cloud, causing the cosmic ray particle to experience mirroring. The characteristic time for the reflection of cosmic rays by this process is [5]

$$t_m \sim \frac{\gamma_m p}{p} \left( \frac{\partial \ln B}{\partial s} \right)^{-1} \sim \frac{\gamma_m L_B}{p},$$

(7)

where $L_B$ is the length along the trajectory of the cosmic ray particle over which the regular component of the magnetic field varies, for which it is natural to adopt $L_B \sim R$. The characteristic diffusion time for the cosmic rays is

$$t_D \sim \frac{R^2}{D}.$$  

(8)

If we suppose that this diffusion is determined by kinetic processes with cross section $\sigma_i \sim 3 \times 10^{-18}$ cm$^2$ (the cross section for ionization losses), the diffusion time will be $t_D = (N\sigma_i)^{3/4}R/c$, so that

$$\frac{t_m}{t_D} \sim \frac{1}{(N\sigma_i)^{3/4}} \ll 1.$$  

(9)

If the diffusion is determined by resonance scattering on small scales of the order of the gyroradius of a cosmic ray proton, $l \sim 2\pi r_p$ [5, 6], the diffusion coefficient will be $D \lesssim c R^{1/4} l^{3/4}$, and the ratio of the time scales becomes

$$\frac{t_m}{t_D} \sim \left( \frac{l}{R} \right)^{3/4} \ll 1.$$  

(10)

Thus, cosmic rays should be reflected by the enhanced magnetic field of a molecular cloud appreciably more rapidly than they can penetrate into the cloud interior. The fraction of cosmic rays that are able to penetrate into the cloud can be crudely estimated using the ratio $t_m/t_D$, which is to
order of magnitude $10^{-3}$ in both cases. This analysis forces us to conclude that the primary ionization rate of the molecular gas is substantially lower than the value that is required in order for the gas–chemical reactions in the cloud to be sustained: $\zeta \sim 10^{-17} \text{ s}^{-1}$. Indeed, galactic cosmic rays with the spectrum presented above provide to order of magnitude just this primary ionization rate. Even if about 10% of the high-energy particles can penetrate into the cloud, which could with some margin lead to agreement between $\dot{E}_{MC}^{\gamma}$ and $\dot{E}_{SN}^{\gamma}$, $\zeta$ would be at least an order of magnitude lower than the required value. This contradiction can be resolved assuming that turbulent motions in the molecular clouds are able to accelerate nonthermal particles to sufficiently high energies to sustain the required level of primary ionization.

4 Acceleration of nonthermal particles in molecular clouds

Molecular clouds display well-developed turbulence, as a rule, supersonic, and apparently super-Alfvénic (see the discussions in [4, 12, 20]). It is, accordingly, natural to expect the presence of numerous MHD shock waves in the cloud, as is observed in both numerical simulations (see the discussion in [21]) and in real molecular clouds [22, 23]. The characteristic velocities of MHD shocks in molecular clouds can reach $\sim 10 \text{ km s}^{-1}$, in which case it is reasonable to expect that some fraction of their kinetic energy could be transformed into nonthermal particles accelerated in the shock fronts. The efficiency of particle acceleration under these conditions can be estimated using the theory developed in the studies [24–27], which are concerned with the acceleration of particles in the fronts of chaotic shocks in turbulent interplanetary and interstellar fields. In this theory, the maximum energy that can be gained by particles is determined by the ratio of the time over which the acceleration region exists (the time for the shocks to travel through the distance separating them), $t_a \sim L_s/u$, and the time for the diffusion of the particles from the acceleration region, $t_D \sim L_s^2/D$, where $L_s$ is the characteristic distance between the shock fronts and $u$ is the shock velocity [26] (the accelerated particles leave the acceleration zone when $t_D/t_a < 1$). The diffusion coefficient $D = v\Lambda/3$ is determined by the scattering of particles on small-scale inhomogeneities in the magnetic field with a characteristic transport free path $\Lambda \simeq C_\nu L_s (r_p/L_s)^{2-\nu}$, where $C_\nu \simeq 0.3$, $r_p = cp/eB$ is the gyroradius of the particle, $p$ is the momentum of the particle, and $\nu$ is the
index of the spectrum of the small-scale fluctuations of the magnetic field \(\langle B^2 \rangle / dk \sim k^{-\nu}, kL_s \gg 1 [26, 27]\). We will estimate the maximum energy of the accelerated particles \(E_M\) from the condition \(t_D/t_a = 1\). This yields for the spectral index \(\nu = 1.5\)

\[
E_M \sim 5 \times 10^{-3} L_{s,R}^2 B_1^2 R_1^2 \text{ GeV}, \tag{11}
\]

when \(E_M < m_p c^2\) and

\[
E_M \sim 0.1 L_{s,R} B_1 R_1 \text{ GeV}, \tag{12}
\]

when \(E_M > m_p c^2\); here, \(L_{s,R} = L_s/R, R_1 = R/(1 \text{ pc}), B_1 = B/(1 \mu \text{ G})\). Thus, in clouds with characteristic parameters \(B \sim 10\mu \text{ G}\) and \(R \sim 10 \text{ pc}\) and with \(L_s/R \sim 0.01 - 0.03\), we expect protons to be accelerated to energies \(E_M \sim 5 - 15 \text{ MeV}\). However, \(E_M\) is very sensitive to the index of the magnetic field fluctuation spectrum \(E_M \propto (u/c)^{1/(2-\nu)}\) in the relativistic limit and \(E_M \propto (u/c)^{2/(2-\nu)}\) in the nonrelativistic case. Therefore, with a Kolmogorov turbulence spectrum, \(\nu \simeq 1.7\), and shock velocities \(u \sim 10 \text{ km s}^{-1}\), the estimates of \(E_M\) fall to values of the order of atomic energies. From this point of view only detailed observations of the magnetic field fluctuation spectrum will enable confident conclusion of whether or not nonthermal particles can be accelerated to sufficiently high energies in molecular clouds. Recent numerical simulations of MHD turbulence in molecular clouds suggest that, in most cases, a Kolmogorov spectrum is established near wavenumbers \(kL/2\pi \sim 10\), but the spectrum becomes appreciably non-Kolmogorov at longer wavelengths (exceeding 0.1 of the cloud radius), where it has an index near zero [12, 13]. Thus, the transition from large scales, corresponding to the energy injection scales, to the scales on which an inertial regime is established encompasses a broad wavenumber range. If we associate the possibility of generation of cosmic rays with long-wavelength components of the turbulent motions in the molecular cloud, the energy \(E_M\) could reach values of 1 GeV or higher. However, both the steady state characteristic energy of the nonthermal particles \(E_s\) and the spectrum of the generated cosmic rays are determined to a considerable extent by the injected particle distribution function – i.e., by those particles that, having entered in an active acceleration region, are able to undergo fairly frequent interactions with the shocks there – and by the fraction \(\eta\) of the injected particles in the flow as a whole that intersect the shock front. One source of particles that is usually considered is the particles that become extracted
from the thermal background during the scattering of fairly energetic protons on forming collisionless shocks. This process is probably not efficient in molecular clouds, because the thermal energy of the particles here is too low. Winds from young stars and/or low-energy cosmic rays entrained in the converging flows forming the molecular cloud may serve as a source of such particles. In any case, the question remains open and requires a separate analysis; more detailed discussions in application to shocks from supernovae and to the diffuse interstellar and interplanetary media can be found in [24, 26, 28, 29]. The value of the fraction of interacting injected particles \( \eta \) is very uncertain. The injection rate at the bow shock in the magnetosphere of the Earth is \( \eta \sim 10^{-3} \) [30]. Estimates carried out in [31] for supernova remnants leave open a very wide range for \( \eta \): \( 10^{-5} < \eta < 10^{-1} \).

If we adopt the lower limit for molecular clouds, the characteristic energy of the nonthermal particles proves to be too low. Based on the fact that the characteristic energy of the nonthermal particles should be such that their total energy \( W_p \sim \eta n p^2/2m_p \) does not exceed the kinetic energy of the generated turbulent motions \( W_T \sim \rho u^2/2 \), we arrive at the estimate \( E_* \lesssim 0.5\eta^{-1}m_pc^2(u/c)^2 \sim 50 \) keV. The Larmor radius of protons with such energies is only \( r_p \sim 3 \times 10^9 \) cm in a magnetic field of \( B \sim 10\mu \) G, so that the protons should primarily occupy a limited volume near the surface of the accelerating shock.

To estimate the primary ionization rate provided throughout the molecular cloud by the generated nonthermal particles, we suppose that only those particles that at times \( t \sim t_a \) have diffusion lengths equal to half the distance between the shock fronts (i.e., \( L_{s,R} = 1/2 \)) are able to occupy the cloud volume fairly uniformly and contribute to the ionization of the medium in the cloud. Adopting a power-law spectrum for the nonthermal particles, \( dN_p/dE \propto E^{-q} \), and assuming that the total energy contained in these particles is comparable to the energy of the turbulent motions, \( \int E dN_p \sim W_T \), we obtain the primary ionization rate

\[
\zeta = \int_{E_{M/2}}^{E_M} v(E) \frac{dN_p}{dE} \sigma(E) dE \simeq 3 \times 10^{-18} n \text{ s}^{-1},
\]

for \( q = 2 \) and

\[
\zeta \sim 3 \times 10^{-19} n \text{ s}^{-1},
\]

for \( q = 2.5 \); here, \( n \) is the gas density in the molecular cloud. Thus, for
a mean gas density $n \sim 10^2 \text{ cm}^{-3}$ [32], we find $\zeta \sim 10^{-17} - 10^{-16} \text{ s}^{-1}$, which is close to the value required to sustain the gas-phase chemistry in the molecular clouds. Note that larger values exceed the value expected from galactic cosmic rays. It is worth stressing in this connection that recent observations of some molecular clouds require primary ionization rates that cannot be provided by galactic cosmic rays. In particular, the value $\zeta = 5.6 \times 10^{-17} \text{ s}^{-1}$ with an uncertainty factor of about three is preferred in [33]; i.e., the upper end of the allowed interval corresponds to $\zeta \sim 10^{-16} \text{ s}^{-1}$. However, even the most probable value exceeds the value expected from galactic cosmic rays by a factor of five. This can be considered as an additional argument for the need for additional sources of cosmic rays in molecular clouds and the possible generation of cosmic rays inside them.

5 Conclusions

We have shown the following:

1. The energy lost by galactic cosmic rays in molecular clouds may exceed the total energy converted into cosmic rays by supernovae.
2. An appreciable fraction of cosmic rays with energies $E \sim 1 \text{ GeV}$ can be reflected from the surface layers of molecular clouds through mirror effect. Thus, an additional source of nonthermal particles is required to sustain the gas-phase chemical processes occurring in these clouds.
3. One such source is particles accelerated on the fronts of MHD shocks that arise during the formation of molecular clouds. The primary ionization rate that can be provided by such particles is $\zeta \sim 10^{-17} - 10^{-16} \text{ s}^{-1}$.

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References

1. W. D. Watson, Rev. Mod. Phys. 48, 513 (1976).
2. E. J. O’Donnell and W. D. Watson, Astrophys. J. 191, 89 (1974).
3. J. Barsuhn and C. M. Walmsley, Astron. Astrophys. 54, 345 (1977).
4. P. C. Myers and V. K. Khersonsky, Astrophys. J. 442, 186 (1995).
5. C. J. Cesarsky and H. J. Völk, Astron. Astrophys. 70, 367 (1978).
6. T. Nakano and E. Tademaru, Astrophys. J. 173, 87 (1972).
7. J. A. Simson, Ann. Rev. Nucl. Part. Sci. 33, 330 (1983).
8. C. F. McKee, in: The Origin of Stars an Planetary Systems, Ed. by C. J. Lada and N. D. Kylafis (Kluwer Acad., 1999), p. 29.
9. M. H. Heyer and S. Terebey, Astrophys. J. 502, 265 (1998).
10. E. Falgarone and J.-L. Puget, Astron. Astrophys. 162, 235 (1986).
11. R. Schlickeiser, Cosmic Ray Astrophysics (Springer, Berlin, 2002).
12. J. Cho and A. Lazarian, Phys. Rev. Letters 88, 245001 (2002).
13. J. G. Vestuto, E. C. Ostriker, and J. M. Stone, Astrophys. J. 590, 858 (2003).
14. J. Ballesteros-Paredes, E. Vázquez-Semadeni, and J. Scalo, Astrophys. J. 515, 286 (1999).
15. E. Vázquez-Semadeni, in: New Perspectives in the Interstellar Medium, Ed. by A. R. Taylor, T. L. Landecker, and G. Joncas (Astron. Soc. Pacif., San Francisco, 1999), ASP Conf. Ser. 168, p. 345.
16. W.-T. Kim, E. C. Ostriker, and J. M. Stone, Astrophys. J. 581, 1080 (2002).
17. R. S. Klessen, Rev. Mod. Astron. 16 (2003).
18. J. P. Phillips, Astron. Astrophys., Suppl. Ser. 134, 241 (1999).
19. F. J. Vrba, S. E. Strom, and K. M. Strom, Astron. J. 96, 680 (1988).
20. S. Boldyrev, Astrophys. J. 569, 841 (2002).
21. P. Padoan, A. A. Goodman, and M. Juvela, Astrophys. J. 588, 881 (2003).
22. E. Falgarone, J.-L. Puget, and M. Perault, Astron. Astrophys. 257, 715 (1992).
23. P. C. Myers and C. F. Gammie, Astrophys. J. 522, L141 (1999).
24. I. N. Toptygin, Cosmic Rays in Interplanetary Magnetic Fields (Reidel, Dordrecht, 1985; Nauka, Moscow, 1983).
25. A. M. Bykov and I. N. Toptygin, Zh. Eksp. Teor. Fiz. 98, 1255 (1990) [J. Exp. Theor. Phys., 98, (1990)].
26. A. M. Bykov and G. D. Fleishman, Pis’ma Astron. Zh. 18, 234 (1992) [Astron. Lett. 18, 95 (1992)].
27. A. M. Bykov and G. D. Fleishman, Mon. Not. R. Astron. Soc. 255, 269 (1992).
28. D. C. Ellison and D. Eichler, Astrophys. J. 286, 691 (1984).
29. R. Blandford and D. Eichler, Phys. Rep. 154, 2 (1987).
30. M. A. Lee, J. Geophys. Res. 87, 5063 (1982).
31. L. O’C. Drury, W. J. Markiewicz, and H. J. Völk, Astron. Astrophys. 225, 179 (1989).
32. J. Bally, in: Galactic Structure, Stars an the Interstellar Medium. ASP Conf. Ser, Eds. C. E. Woodward, M. D. Bicay, and J. M. Shull (Astron. Soc. Pacif., San Francisco, 2001), ASP Conf. Ser. 231, p. 204.
33. S. D. Doty, E. F. van Dishoeck, F. F. S. van der Tak, and A. M. S. Boonman, Astron. Astrophys. 389, 446 (2002).