Electron and Ion Densities in Interstellar Clouds

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ABSTRACT

A quantitative theory of ionization in diffuse clouds is developed which includes H^+ charge exchange with O. Dissociative charge exchange of He^+ with H_2 plays an important role in the densities of H^+ and He^+. The abundance of HD is also discussed.

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I. Introduction.

The densities of electrons and ions play an important role in determining the physical and chemical properties of interstellar clouds. In this article we present a theory for the ionization of interstellar clouds which should be applicable to diffuse and moderately thick clouds (column densities $N \lesssim 7 \times 10^{21} cm^{-2}$). This work is an extension of our recent discussion of ionization in diffuse clouds (Glassgold and Langer 1974, especially Appendix A).

There are two main sources of electrons in interstellar clouds: the ionization by the radiation field of heavy trace elements with ionization potentials $I < 13.6$ eV (e.g. carbon), and cosmic ray ionization of atomic and molecular hydrogen and helium. In addition to radiative recombination, ions are removed by charge exchange, dissociative recombination, and ion-molecule reactions. The last two types of reactions become important as soon as the interstellar clouds contain an appreciable amount of molecular hydrogen. Charge exchange and ion-molecule reactions only affect the electron density indirectly, in that the transformation of one ion into another affords the possibility of a different recombination process. In particular, the rate constant for dissociative recombination is many orders of magnitude larger than that for radiative recombination. Field and Steigman (1971) pointed out that charge exchange of H^+ with atomic oxygen is important in determining the ionization of the interstellar medium. When molecular hydrogen is present in interstellar clouds, the O^+ produced by charge exchange interacts with H_2 to form OH^+, and in subsequent interactions with H_2 and electrons a variety of oxygen bearing molecules and molecular ions are formed. The primary effect of these reactions is to remove H^+ and electrons at a greater rate than if only radiative recombination were operative (Dalgarno, Oppenheimer, and Berry, 1973; Watson, 1973; and Black and Dalgarno, 1973). The exact rate depends sensitively on temperature since $O + H^+$ charge exchange is endothermic by $232^{\circ}K$. Some of the molecules formed from the chain beginning with O^+, namely OH and H_2O, can charge exchange exothermically with H^+ and He^+, but their effect can be neglected if $n(OH)/n(O)$ and $n(H_2O)/n(O) < 10^{-2}$.

We also include a reaction which has not been previously considered in problems of this type, dissociative charge exchange of He^+ and H_2,

$$He^+ + H_2 \rightarrow H + H^+ + He \tag{1}$$

The rate constant for this reaction has recently been measured as $\sim 10^{-13} cm^3 s^{-1}$ (Biondi, 1974). Despite this low value, reaction (1) is an important source of H^+ when the fractional abundance of H_2 is high ($f > 0.6$) and it can dominate the recombination of He^+ even for small values of f. The parameter f is defined in terms of the atomic and molecular hydrogen densities,

$$f = 2n(H_2)/n \qquad n = n(H) + 2n(H_2) \quad . \tag{2}$$

Deuterium also can charge exchange with H^+,

$$D + H^+ \rightarrow H + D^+, \tag{3}$$

but this does not lead to a significant reduction in $n(H^+)$ since D^+ reacts rapidly with H and H_2 to produce H^+ again,

$$D^+ + H \rightarrow H^+ + D \tag{4}$$

$$D^+ + H_2 \rightarrow HD + H^+ \tag{5}$$

The HD density, n(HD), can be used to estimate the primary cosmic ray ionization rate on hydrogen, ζ_p, through its connection to H^+ via reactions (3) and (5) (Black and Dalgarno, 1973; Jura, 1974; O'Donnell and Watson, 1974).

In this article we will discuss quantitatively the role charge exchange and related ion-molecule reactions play in the electron, H^+, and HD abundances for diffuse and moderately thick clouds. The results will depend on a number of physical parameters of the cloud, such as temperature T, density n, molecular hydrogen fraction f, and heavy element abundances ξ. The H^+ concentration is crucial for the production of interstellar molecules through gas-phase ion-molecule reactions. The electrons are important in determining the recombination of all ions and thus the abundances of all species which are substantially ionized. Finally, the electron density is also basic in the thermal balance of the cloud because electrons collisionally excite and de-excite cooling transitions.

II. Calculation

The electron and ion abundances will be determined by solving the chemical balance equations for all the constituents, using the constraints of charge neutrality and conservation of number density for each nuclear species. The problem is very complex, but it can be solved approximately in a number of different limits. We restrict ourselves to a regime characteristic of many of the clouds which have recently come under study, namely diffuse to moderately thick clouds with $E(B - V) \lesssim 2$. These clouds are relatively cool ($T \lesssim 100^\circ$ K) and contain substantial amounts of molecular hydrogen ($f \gtrsim 0.1$). Extensive observations have recently been made on diffuse clouds with the Princeton UV spectrometer on the Copernicus spacecraft. The H_2 column densities deduced indicate that f = 0.1 is reached when the total hydrogen column density into the cloud, $N = N[H] + 2N[H_2]$, becomes $\gtrsim 5 \times 10^{19} cm^{-2}$. This result is supported by theoretical studies (Hollenbach, Werner, and Salpeter, 1971; Glassgold and Langer, 1973a and 1974; Jura, 1974). Kinetic temperatures in the range from 70 - 120°K have been determined for these clouds from the relative populations of the lowest J = 0 and 1 states of H_2 (Spitzer and Cochran, 1973; Spitzer, Cochran, and Hirshfeld, 1974). The temperatures in somewhat thicker clouds may be expected to be lower because of the attenuation of external heating radiations. Thus we are interested in determining the electron and ion abundances in regions where the interstellar gas is predominantly a mixture of He, H, and H_2 with $f \geq 0.1$, $T \lesssim 100°K$, and where cosmic rays make some contribution to the ionization rate.

In Table I we list the main reactions which determine the ion and HD abundances in the clouds under consideration. The rates for cosmic ray ionization of H, H_2, and He include direct ionization by the cosmic rays and ionization by secondary electrons (Glassgold and Langer, 1973b, 1974). The charge exchange reactions remove and return the ions H^+, D^+, and O^+. Next listed are the ion-molecule reactions which make H_3^+, HD, and OH^+; OH^+ subsequently reacts to form other oxygen-bearing molecules and molecular ions. The dissociative charge exchange reaction of He^+ with H_2 dominates over other H^+-producing reactions with molecules because the large abundance of H_2 more than compensates for the small rate constant k_9. Thus the fast reaction $C^+ + OH \rightarrow CO + H^+$ (Herbst and Klemperer, 1973; O'Donnell and Watson, 1974) cannot compete with k_9 until the fractional abundance of OH becomes as large as $10^{-4}\ \xi(He^+)/\xi(C^+)$, where $\xi(He^+)$ and $\xi(C^+)$ are the fractional abundances of He^+ and C^+. For diffuse and moderately thick clouds, this would require $\xi(OH) \sim 10^{-5}$, which is unreasonably large. We have also omitted other H^+-destroying charge exchange reactions with neutral molecules for similar reasons, i.e. because the relevant molecular abundances are too small in the clouds under consideration. For example, the rate constants for $H^+ + OH \rightarrow H + OH^+$ and $H^+ + H_2O \rightarrow H + H_2O^+$ are probably $\sim 10^{-9} cm^3 s^{-1}$, and thus these reactions destroy H^+ at a rate 10-100 times slower than does charge exchange with O for temperatures in the range from 50-100°K. Our estimates on the abundances of the various oxygen molecules are based on a related investigation which we are now preparing for publication. In this work we also find that the densities of molecular ions such as OH^+, H_2O^+, and H_3O^+ are negligible compared to the total ion density. Charge exchange and other ion-molecule reactions initiated by other atomic ions such as C^+, He^+, etc. can be ignored for similar reasons.

The chemical balance equations for O^+, D^+, He^+, H_3^+, and H^+ yield the following relations:

$$n(He^+) = \frac{\zeta(He)\ \xi(He)n}{\alpha(He^+)n_e + k_9 n(H_2)} \tag{6}$$

$$n(O^+) = \frac{k_5 \xi(O)n\ n(H^+)}{k_6 n(H) + k_8 n(H_2)} \tag{7}$$

$$n(D^+) = \frac{k_3\ \xi(D)n\ n(H^+)}{k_4 n(H) + k_7 n(H_2)} \tag{8}$$

$$n(H_3^+) = \frac{k_2\zeta_2(H_2^+)\, n^2(H_2)}{\beta(H_3^+)\, n_e\left[k_1 n(H) + k_2 n(H_2)\right]}$$

and, for H^+,

$$n(H^+) = \frac{\zeta_H n + k_9 n(He^+)\, n(H_2)}{\alpha(H^+)\, n_e + \gamma\, n} \quad , \tag{10}$$

where

$$\zeta_H = \left[\zeta_1 + \frac{k_1\, f/2}{k_1 + (k_2/2 - k_1)f}\right](1 - f) + \zeta_2(H^+)f/2, \tag{11}$$

$$\gamma = \frac{k_8}{2\,k_6 + (k_8 - 2k_6)\,f}\; k_5\, \xi(0)\, f \;, \tag{12}$$

and $\xi(He)$, $\xi(0)$, and $\xi(D)$ are total fractional abundances relative to hydrogen. (Thus we have anticipated the conclusions implied by (6) - (8) that He, O, and D are mainly neutral for the clouds under consideration.) On the other hand, we take the elements with $I < 13.6$ eV to be predominantly ionized, which requires $N < 7 \times 10^{21}\,cm^{-2}$, assuming the ionizing radiation to be attenuated by a grain cross section of $1.25 \times 10^{-21}\,cm^2$ per interstellar hydrogen atom. If ξ_i is the total relative abundance of these elements, the total heavy ion density is

$$n_i = \xi_i\, n \;,$$

and the electron density is

$$n_e = n(H^+) + n(He^+) + n_i \quad . \tag{13}$$

The relative abundances of H_2^+ and H_3^+, as well as all other atomic and molecular ions, are too small ($\lesssim$ 5 x 10^{-6}) to be included in (13). An equation for the fractional abundance of electrons, $x_e = n_e/n$, is obtained by substituting (6) and (10) into (13),

$$x_e^2 - (\xi'_i - \frac{\gamma}{\alpha})x_e - (\frac{\gamma}{\alpha} \xi'_i + \frac{\zeta'_H}{n\,\alpha}) = 0 \ , \tag{14}$$

where $\alpha = \alpha(H^+)$ and

$$\xi'_i = \xi_i + x(He^+) \tag{15}$$

and

$$\zeta'_H = \zeta_H + k_9 \ \frac{f}{2} \ x(He^+)n \quad . \tag{16}$$

Equation (14) is a cubic because of the $\alpha(He^+)\, x_e$ term in the denominator of (6), but it can be simplified in a number of physically interesting cases.

When $\alpha(He^+)\, x_e << k_9\, f/2$, (14) becomes a quadratic with the solution:

$$x_e = 1/2 \left[(\xi'_i - \frac{\gamma}{\alpha}) + \sqrt{(\xi'_i + \frac{\gamma}{\alpha})^2 + 4\, \zeta'_H/n\alpha} \right] . \tag{17}$$

$$x(H^+) = 1/2 \left[-\left(\xi'_i + \frac{\gamma}{\alpha}\right) + \sqrt{\left(\xi'_i + \frac{\gamma}{\alpha}\right)^2 + 4\zeta'_H/n\alpha} \right]. \quad (18)$$

Using the values for $\alpha(He^+)$ and k_9 in Table I, the condition for ignoring radiative recombination of He^+ is $f >> 200\ x_e$ for temperatures in the range from 50-100°K. Since x_e is roughly of the order of 10^{-4} provided $\zeta_p \lesssim 10^{-16} s^{-1}$, (17) and (18) will apply as soon as a moderate fraction of hydrogen has been converted to molecular form, say $f \approx 0.1$.

When He^+ radiative recombination can not be ignored, the ionization equations can be solved by iteration on the following system of equations:

$$x_e = 1/2 \left[\left(\xi_i - \frac{\gamma}{\alpha}\right) + \sqrt{\left(\xi_i + \frac{\gamma}{\alpha}\right)^2 + 4\left(\zeta'/n\alpha + \frac{\gamma}{\alpha}\, x\,(He^+)\right)} \right] \quad (19)$$

$$x(He^+) = \frac{\xi(He)\ \zeta(He)/n}{\alpha\ x_e + k_9\ f/2} \quad (20)$$

$$x(H^+) = x_e - x(He^+) - \xi_i\ , \quad (21)$$

where

$$\zeta' = \zeta_H + \xi(He)\ \zeta(He) \quad (22)$$

and where we have used $\alpha(He^+) = \alpha(H^+) = \alpha$. Eq. (18) suggests another approximate solution,

$$x_e \cong 1/2 \left[(\xi_i - \frac{\gamma}{\alpha}) + \sqrt{(\xi_i + \frac{\gamma}{\alpha})^2 + 4\,\zeta'/n\alpha} \right] \tag{23}$$

$$x(H^+) \cong 1/2 \left[-(\xi_i + \frac{\gamma}{\alpha}) + \sqrt{(\xi_i + \frac{\gamma}{\alpha})^2 + 4\,\zeta'/n\alpha} \right] \tag{24}$$

appropriate for $x(He^+) << \zeta'/n\gamma$. Referring to (22) and (11) for ζ' and (12) for γ, we can see that this approximation tends to improve as T and $\xi(0)$ are decreased. In fact this approximation works very well over the ranges of parameters considered in this work and is generally superior to (17) and (18).

Electron and ion abundances are plotted in Figure 1 as a function of f for a typical parameter set: $n = 100\ cm^{-3}$, $T = 80^oK$, $\zeta_p = 10^{-16}s^{-1}$, $\xi(0) = 10^{-4}$, $\xi_i = 7 \times 10^{-5}$ (corresponding to heavy element depletion by a factor $\sim$ 7). The He^+ fractional abundance decreases rapidly with f (increasing H_2 abundance) as a result of dissociative charge exchange. Because this reaction produces H^+ ions, $x(H^+)$ does not decrease rapidly until f becomes large ($\gtrsim 0.8$). The rapid decrease occurs because of (i) the disappearance of direct cosmic ray ionization of H (c.f. the first term in (11)), (ii) the smallness of dissociative ionization of H_2 (the second term in (11)), and (iii) $O^+ + H_2 \rightarrow OH^+ + H$ competes with $O^+ + H \rightarrow O + H^+$. The changes induced in Figure 1 by changes in parameters can be understood from (23) and (24) in terms of the two most important variables, $\zeta_p/n\alpha$ and $\gamma \sim 10^{-9} e^{-232/T}\ \xi(0) f\ cm^3 s^{-1}$.

The appearance of H_3^+ in Figure 1 for large f is important because H_3^+ enters into numerous ion-molecule reactions (Herbst and Klemperer, 1973; Watson, 1973). In the context of the present discussion, H_3^+ reacts exothermically with O to produce OH^+ and H_2O^+ at a rate $\sim 10^{-9}cm^3s^{-1}$, and thus competes with endothermic $H^+ + O$ charge exchange ($k_5 \sim e^{-232/T}10^{-9}cm^3s^{-1}$) when $f \gtrsim 0.8$ and $T \lesssim 100^oK$, even though it is only $\sim 1/10$ as abundant as H^+. The relative importance of H^+ and H_3^+ depends on n, T, and $\xi(O)$. For example, in a denser region where $n = 10^3 cm^{-3}$, $T = 80^oK$, $\zeta_p = 10^{-16}s^{-1}$, and $\xi(O) = 10^{-4}$, $x(H_3^+) = 0.1\ x\ (H^+)$ for $f = 0.7$ and $x(H_3^+) = x(H^+)$ for $x = 0.95$. At lower temperatures, H_3^+ will be even more important.

The reduction in the He^+ abundance by dissociative charge exchange with H_2 has other implications for the ion-molecule reaction chemistry of the interstellar gas. Herbst and Klemperer (1973) assumed that He^+ is destroyed in dense clouds by dissociative charge exchange with CO,

$$He^+ + CO \rightarrow C^+ + O + He, \qquad (25)$$

with a rate constant $2 \times 10^{-9}cm^3s^{-1}$ (Laudenschlager and Bowers, 1973). In order for (25) to compete with (1), the relative CO abundance must be $\sim 10^{-4}$. For smaller CO concentrations, the rate at which He^+ dissociatively charge exchanges with heavier neutral molecules, and thus produces atomic ions, is smaller than previously assumed.

III. Discussion.

The abundance of HD provides a good example of the application of the results of Section II. Unless f is very small ($\lesssim 10^{-3}$), reaction (5) is much more important than grain formation for producing HD. The primary destruction mechanism is photo dissociation

$$h\nu + HD \rightarrow H + D \,, \tag{26}$$

with rate constant η. The balance equations for HD and D^+ (Black and Dalgarno, 1973; Jura, 1974; O'Donnell and Watson, 1974) lead to the relation

$$x(HD) = \frac{k_7}{2\,k_4 + (k_7 - 2\,k_4)f}\; k_3\; \xi(D)\; f\; \frac{x(H^+)\,n}{\eta} \quad . \tag{27}$$

We use the results of Section II to obtain the curves of Figure 2, using the parameters $n = 10^2 cm^{-3}$, $\xi(D) = 1.5 \times 10^{-5}$ (Rogerson and York, 1973), $\xi(O) = 10^{-4}$, $\xi_i = 7 \times 10^{-5}$, and $\eta = 10^{-10} s^{-1}$. This value for η is based on the calculations of Stephens and Dalgarno (1972) and the average interstellar radiation field given by Jura (1974). The solid curves are for 80°K and a range of primary ionization rates, $\zeta_p = 10^{-17}$, 5×10^{-17}, and $10^{-16} s^{-1}$. The existence of a strong maximum for x(HD) at an intermediate value of f occurs from the competition between the f-increasing coefficients in (27) and $x(H^+)$, which is a strongly decreasing function of f as $f \rightarrow 1$. In applying these curves to cloud models, variations in physical properties of the clouds must be taken into account, such as density, temperature, radiation field, and size. For example, grain attenuation of the UV radiation field near 1000 Å reduces the dissociation rate η, roughly as

$$\eta \simeq \eta_o\, e^{-\tau} \qquad\qquad \tau \simeq N(8 \times 10^{20} cm^{-2})^{-1} \quad . \tag{28}$$

This decrease in η tends to compensate for the decrease in $x(H^+)$, and thus to extend the region in which HD occurs with substantial abundance.

The two dashed curves in Figure 2 indicate the effects of varying the temperature for the particular case $\zeta_p = 5 \times 10^{-17} s^{-1}$. The values 60, 80, and 100°K roughly cover the range in kinetic temperatures observed for diffuse clouds (Spitzer and Cochran, 1973; Spitzer et al, 1974). The HD fraction is seen to change by as much as a factor of two for large f. The main source of the temperature variation is the $e^{-232/T}$ factor in the $H^+ + O$ charge exchange rate constant k_5 occurring in γ (Eq. (12)), which appears in the $x(H^+)$ formula (24).

In order to discuss the HD column density measurements of the Princeton group (Spitzer et al, 1973 and 1974), it is useful to rewrite (27) in terms of the HD-H_2 fraction $y \equiv n(HD)/n(H_2)$,

$$y = \frac{2k_7}{2k_4 + (k_7 - 2k_4)f} k_3 \, \xi(D) \frac{x(H^+) n}{\eta} \quad . \qquad (29)$$

The advantage of (29) is that most of the variations in the members of the right side tend to cancel for diffuse clouds. This can be seen in Figure 3, where y is plotted as a function of f for a number of choices of ζ_p, $n = 20$ and 100 cm^{-3}, and for common values $T = 80°K$, $\xi(O) = 10^{-4}$, $\xi_i = 5 \times 10^{-7}$, and $\eta = 10^{-10} s^{-1}$. We note that y is roughly constant for $f < 0.6$ and $\zeta_p/n > 5 \times 10^{-19} \text{cm}^3 s^{-1}$. Furthermore, when y is changed from 20 to 100 cm^{-3} (corresponding to a reasonable density range for diffuse clouds, Glassgold and Langer, 1973a, 1974; Jura, 1974), y changes by at most a factor of 2. According to our earlier model calculations, n does not vary by more than a factor of 2 and T changes little in going from the outside to the inside of a diffuse cloud. Thus we can ignore the variation of y with n and T. On the other hand, UV attenuation (28) can be important, depending on the column density N into the cloud. The effect of decreasing η may be crudely viewed as a raising of the large f portions of the curves of Figure 3 so as to maintain y roughly constant up to $f \sim 0.8 - 0.9$. To summarize, (29) together with the ionization formulae (24), provide justification for replacing $y = n(HD)/n(H_2)$ by the column density ratio $Y \equiv N[HD]/N[H_2]$, as was done in previous work (Black and Dalgarno, 1973; Jura, 1974; O'Donnell and Watson, 1974). The measurements of Y (Spitzer et al, 1973, 1974) vs. $F = 2N[H_2]/N$ have also been included in Figure 3 mainly for reference, and not for purposes of direct comparison with the theoretical curves of y vs. f. A proper comparison can only be made in terms of a more complete (inhomogeneous) model calculation for Y vs. N, such as we recently reported for H_2 and other species (Glassgold and Langer, 1974). On the other hand, it is interesting that a number of the measurements of Y cluster about the value 8×10^{-7}, and that the deviations for 59 Cyg and ζ Oph may be partly understood in terms of variations in the relevant radiation field (Jura, 1974). O'Donnell and Watson (1974) have proposed a similar explanation for the anomalously large value of Y measured for 10 Lac.

Proceeding on the basis that $y \simeq Y =$ constant for a diffuse cloud, we can invert (29) and obtain a rough formula for the dependence of $n(H^+)$ on N and f,

$$n(H^+) \simeq \left[k_7/k_4 + (1/2 - k_4/k_7)f\right] k_3^{-1} \xi(0)^{-1}\, \eta_0 e^{-N(8 \times 10^{20} cm^{-2})^{-1}}\, Y. \quad (30)$$

According to this result, substantial reductions are possible for $n(H^+)$ in going from the outside to the inside of a cloud, in part from attenuation and in part from the coefficient in square brackets. The numerical values for $n(H^+)$ obtained from (30) at the center of a diffuse cloud are essentially the same as those obtained by previous authors, i.e. in the range from 10^{-3} - 10^{-2} cm^{-3}.

To conclude this discussion of the HD problem, it must be said that a quantitative understanding of the observations must still be given. We have attempted to emphasize the importance of various inhomogeneities, especially the variation in $x(H^+)$ and the attenuation of the HD photo-dissociation rate. We did find some basis for the possibility that these two effects partly compensate in diffuse clouds, but a more detailed model calculation is really needed. The results of any calculation will be strongly influenced by the radiation field appropriate to each cloud and by the values for rather uncertain charge-exchange and ion-molecule reaction rate constants. The fact that some of the measured values for Y are much larger or much smaller than the average may prove difficult to explain. In view of all these qualifications and uncertainties, we believe that the present HD abundance determinations cannot determine ζ_p to much better than a factor of 5. As previous authors have estimated, ζ_p is likely to lie somewhere in the range from $10^{-17}s^{-1}$ - $10^{-16}s^{-1}$.

The results of Section II also relate to the determination of interstellar cloud electron densities from absorption line measurements. Since we have recently commented on observations of CaI and CaII (White, 1973; Bortolot et al, 1974) and CI and CII (Morton et al, 1973), we note that Hobbs (1973, 1974) and Lutz (1974) have recently made deductions about ionization in clouds from KI absorption lines. Hobbs attempts to draw conclusions about the density variation of x_e and the difference between x_e and $x(H^+)$. He finds that the $n^{-\frac{1}{2}}$ variation of x_e associated with cosmic ray ionization of atomic H is in conflict with KI measurements, and he concludes that $\zeta_p \lesssim 10^{-16} s^{-1}$. The theory of Section II contains a number of improvements in previous discussions of ionization in clouds which are relevant in this connection. In particular, we have included the important H^+ destruction mechanism of charge exchange with O, the suppression of direct ionization of H by the formation of molecular hydrogen, and the transformation of He^+ into H^+ ions by dissociative charge exchange. The latter effects are contained in the effective ionization rates ζ_H' and ζ' defined by (11) and (22), respectively. Taken together with the above discussion of HD (which suggests that ζ_p lies in the range 10^{-17} - 10^{-16} s^{-1}), it does seem on the basis of Eq. (24) that a clear $n^{-\frac{1}{2}}$ variation for x_e will not be manifested in interstellar clouds except for very small densities.

In conclusion, we find that the ionization structure of a diffuse cloud containing moderate amounts of molecular hydrogen is inhomogeneous. Even for the clouds observed by the OAO-3 program, fairly large values of f are appropriate toward their centers, so that much of the variation indicated in Figure 1 may be expected to occur. Additional inhomogeneities arise from the density and temperature variation predicted by model calculations (Glassgold and Langer, 1974).

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Table I.

Reaction	Rate	Reference
Cosmic Ray Ionization		1
$p + H \rightarrow H^+ + e + p$	$\zeta_1 = 1.5\ \zeta_p$	
$p + H_2 \rightarrow H_2^+ + e + p$	$\zeta_2(H_2^+) = 2.3\ \zeta_p$	
$p + H_2 \rightarrow H + H^+ + e + p$	$\zeta_2(H^+) = 0.02\ \zeta_2(H_2^+)$	
$p + He \rightarrow He^+ + e + p$	$\zeta(He) = 1.5\ \zeta_p$	
Charge Exchange		
$H_2^+ + H \rightarrow H_2 + H^+$	$k_1 = 6 \times 10^{-10} cm^3 s^{-1}$	2
$D + H^+ \rightarrow D^+ + H$	$k_3 = 2 \times 10^{-9}\ e^{-43/T} cm^3 s^{-1}$	3
$D^+ + H \rightarrow D + H^+$	$k_4 = 2 \times 10^{-9} cm^3 s^{-1}$	3
$O + H^+ \rightarrow O^+ + H$	$k_5 = 10^{-9} e^{-232/T} cm^3 s^{-1}$	4
$O^+ + H \rightarrow O + H^+$	$k_6 = 10^{-9} cm^3 s^{-1}$	4
Ion Molecule Reactions		
$H_2^+ + H_2 \rightarrow H_3^+ + H$	$k_2 = 2 \times 10^{-9} cm^3 s^{-1}$	5
$D^+ + H_2 \rightarrow HD + H^+$	$k_7 = 10^{-9} cm^3 s^{-1}$	6
$O^+ + H_2 \rightarrow OH^+ + H$	$k_8 = 2 \times 10^{-9} cm^3 s^{-1}$	7
Dissociative Charge Exchange		
$He^+ + H_2 \rightarrow He + H + H^+$	$k_9 = 10^{-13} cm^3 s^{-1}$	8
Radiative and Dissociative Recombination		
$e + H^+ \rightarrow H + \gamma$	$\alpha(H^+) = 1.9 \times 10^{-10} T^{-0.7} cm^3 s^{-1}$	9

(Table 1, contd.)

Reaction	Rate	Reference
$e + He^+ \rightarrow He + \gamma$	$\alpha(He^+) = \alpha(H^+)$	9
$e + H_3^+ \rightarrow 3H$ or $H_2 + H$	$\beta(H_3^+) = 4 \times 10^{-6} T^{-0.5} cm^3 s^{-1}$	10

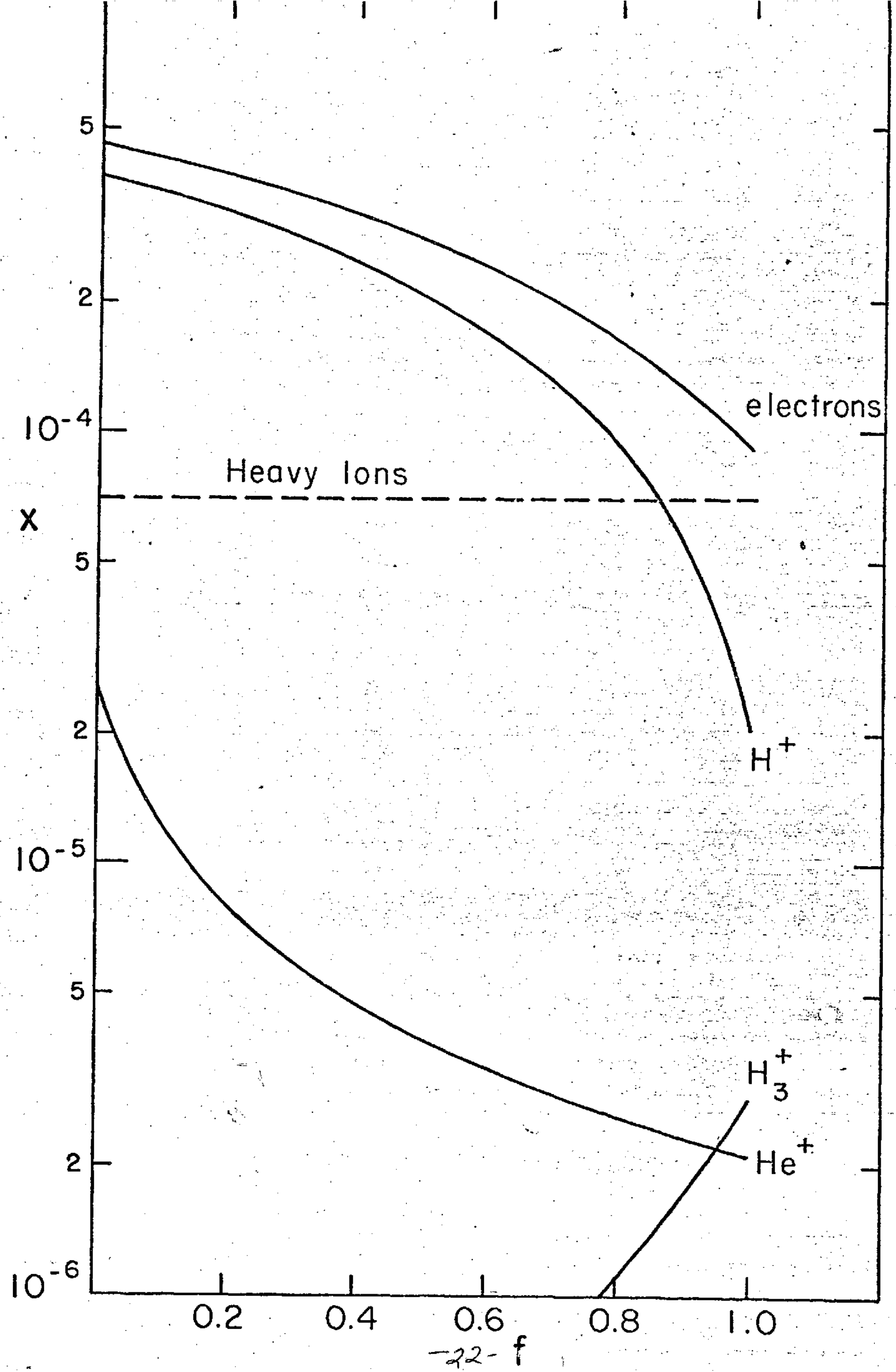
1. Glassgold and Langer (1973)
2. de Jong (1972)
3. Smith (1966)
4. Field and Steigman (1971)
5. Neynaber and Trujillo (1972)
6. Fehsenfeld et al (1973)
7. Fehsenfeld et al (1966)
8. Biondi (1974)
9. Spitzer (1968)
10. Leu, Johnson, and Biondi (1973)

FIGURE CAPTIONS

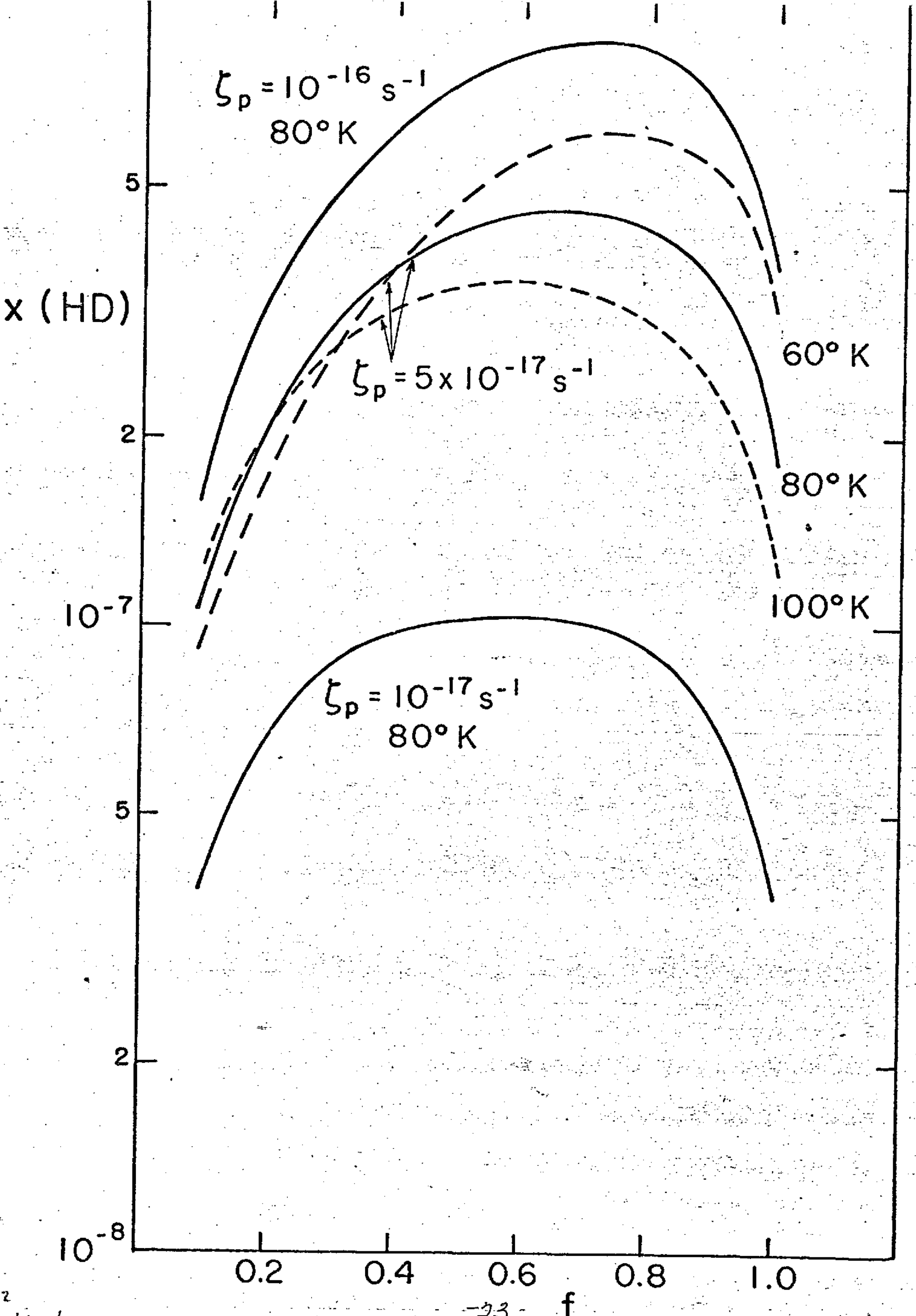
1. Fractional abundances of electrons and various ions as a function of fractional H_2 abundance $f = 2n(H_2)/n$, $n = n(H) + 2n(H_2)$ for $T = 80^{\circ}K$, $n = 100\ cm^{-3}$, $\zeta_p = 10^{-16} s^{-1}$, $\xi(0) = 10^{-4}$, and $\xi_i = 7 \times 10^{-5}$. The dashed line is ξ_i, the fractional abundance of ions of atoms with ionization potential $I < 13.6$ eV.

2. Fractional abundance of H^+ ions as a function of f for $T = 80^{\circ}K$, $n = 100\ cm^{-3}$, $\xi(0) = 10^{-4}$, $\xi_i = 7 \times 10^{-5}$ and $\zeta_p = 10^{-17}$, 5×10^{-17}, and $10^{-16} s^{-1}$ (solid curves). The dashed curves are for $T = 60^{\circ}K$ and $100^{\circ}K$ and $\zeta_p = 5 \times 10^{-17} s^{-1}$.

3. Ratio of HD to H_2 densities, $y = n(HD)/n(H_2)$ as a function of f for $T = 80^{\circ}K$, $\xi(0) = 10^{-4}$, $\xi_i = 7 \times 10^{-5}$, and a range of primary cosmic ray ionization rates ζ_p. The solid curves are for a density $n = 100\ cm^{-3}$, and the dashed curves for $n = 20\ cm^{-3}$. The open circles are the measured ratios of $Y = N[HD]/N[H_2]$ as a function $F = 2N[H_2]/N$, $N = N[H] + 2N[H_2]$ (on the same scale as y and f, respectively) as reported by Spitzer et al (1973, 1974).



5
2
10-4
Heavy Ions
X
electrons
5
2
H+
10-5
5
H3+
2
He+
10-6
0.2
0.4
0.6
0.8
1.0
f



$\zeta_p = 10^{-16}\ s^{-1}$
80° K
x (HD)
$\zeta_p = 5 \times 10^{-17}\ s^{-1}$
60° K
80° K
100° K
$\zeta_p = 10^{-17}\ s^{-1}$
80° K
5
2
10^{-7}
5
2
10^{-8}
0.2
0.4
0.6
0.8
1.0
f

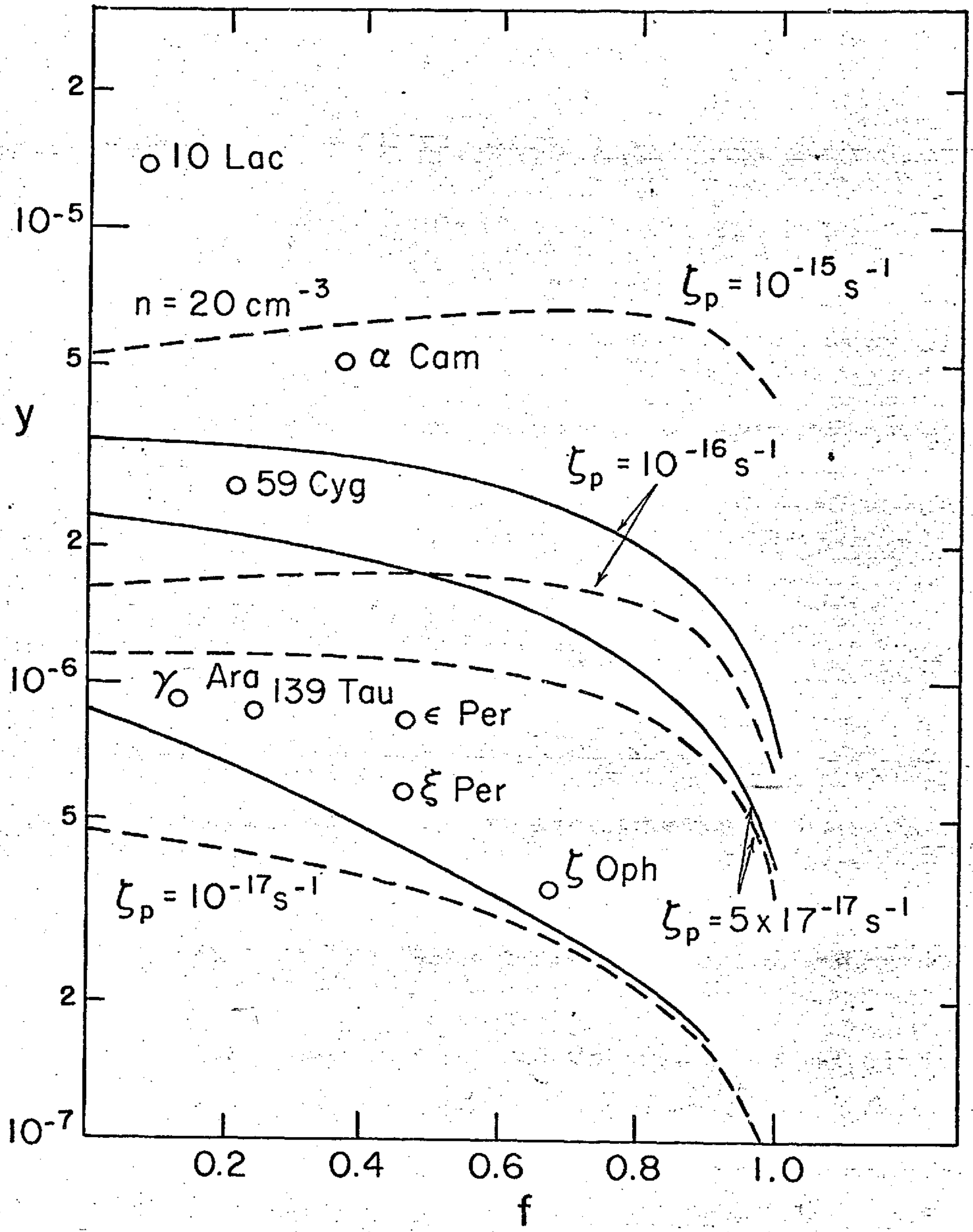


Fig 3
Glassgold
Langer