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$K\alpha$ X-rays From Cosmic Ray Oxygen

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Equilibrium charge fractions are calculated for subrelativistic cosmic ray oxygen ions in the interstellar medium. These are used to determine the expected flux of $K\alpha$-rays arising from atomic processes for a number of different postulated interstellar oxygen spectra. Relating these results to the diffuse X-ray background measured at the appropriate energy (i.e. $\sim$0.6 keV) suggests an observable broadened line feature.

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I. Introduction

As pointed out by Silk and Steigman (1969), charge exchange between subrelativistic cosmic rays and the interstellar gas may lead to detectable X-ray line emission. This paper examines in detail the question of such line flux from cosmic ray oxygen. First, the average yield of Kα X-rays per oxygen nucleus is evaluated. Several possible interstellar cosmic ray oxygen spectra are then used to obtain estimates for the Kα X-ray line flux to be expected. Finally, these estimates are compared to the observed spectrum of the diffuse background at $\sim$0.6 keV.

II. Cosmic Rays in Charge Equilibrium

Subrelativistic cosmic rays created in supernova explosions will be ejected into the interstellar medium at energies of several MeV/nucleon. (cf., Ramaty et al., 1971; Serlemitsos et al., 1973). Initially these nuclei may be stripped of their atomic electrons. However, in passing through the interstellar medium, they will accumulate electrons via the process of charge exchange with the ambient matter. The resulting ions will reach a charge equilibrium, determined solely by their velocity, via the competing processes of electron capture and loss. Equilibrium will be achieved if many charge changing interactions occur during the collision loss lifetime of the cosmic rays. The number of such interactions for each process in passing from E_i to E_f is given by

$$N = \int_{E_i}^{E_f} n \sigma v \left(\frac{dE}{dt}\right)^{-1} dE \qquad (1)$$

with n the target density, σ the interaction cross section, and v the ion velocity. The energy loss per nucleon of a nonrelativistic particle of charge Ze and mass number A in hydrogen is given by (Hayakawa and Kitao, 1956)

$$\frac{dE}{dt} \simeq 1.46 \times 10^{-12} \frac{Z^2}{A} n_H E^{-0.3} \qquad (2)$$

where E is kinetic energy per nucleon in units of MeV. For the relevant cross sections discussed in the appendix equation (1) yields $N \geqslant 100$ for energy per nucleon limits of E_i = 10 MeV to E_f = 1 MeV on the integral.

Oxygen nuclei at energies greater than 10 MeV/nucleon will remain stripped of their electrons in propagating through the interstellar medium. The charge fractions at equilibrium have been calculated for oxygen nuclei at energies below 10 MeV/nucleon and are exhibited in the appendix.

III. $K\alpha$ X-Rays From Oxygen

There are two important processes which result in $K\alpha$ X-ray emission from subrelativistic cosmic ray oxygen in the interstellar gas. The first is the charge exchange of electrons from ambient interstellar matter into excited orbitals of the oxygen nuclei. The captured electron subsequently cascades down to the ground state emitting a characteristic $K\alpha$ X-ray in final transition. For capture to OVIII this line occurs at 0.65 keV and is the analogue of the Lyman alpha line for hydrogen. For capture to OVII the transition corresponds to that for a helium type ion and occurs at 0.56 keV. Captures into excited states lead to the production of $K\alpha$ X-rays approximately 60% of the time (Bethe and Salpeter, 1957, Chapman, 1969).

The second process is collisional excitation of the single electron from the ground state of OVIII to the 2p orbital caused by interstellar hydrogen. This process followed by decay back to the ground state also yields a line at 0.65 keV.

Other mechanisms of lower yield not considered here are 1) excitation of the OVIII electron by other elements of the interstellar medium and to other excited levels, 2) excitation of the OVII electrons by the interstellar medium, and 3) charge exchange of K electrons from OVI and lower charged ions.

Of the two major processes described above the first dominates by about an order of magnitude. For oxygen nuclei the cross sections for both processes peak in the 1-2 MeV per nucleon energy range.

The cross section for charge exchange is given by Schiff (1955); viz:

$$\sigma^{Z}_{i,i-1} = \frac{2^{18}}{5} \pi a_0^2 \frac{i^5}{n^3} Z\left(\frac{V}{V_0}\right)^5 \left[\left(\frac{V}{V_0}\right)^4 + 2\left(\frac{V}{V_0}\right)^2\left(Z^2 + \frac{i^2}{n^2}\right) + \left(Z^2 - \frac{i^2}{n^2}\right)^2\right]^{-5} \quad (3)$$

where i and i-1 are respectively the initial and final ion charges, n is the principal quantum number of the orbital into which the electron is first captured, a_0 is the Bohr radius, Vo the corresponding electron velocity, Z the atomic number of the medium, and V the ion velocity. For the total cross section, equation (3) is summed over all n>1. Most of the captures occur from abundant interstellar species with $Z \leq 8$. (See Table 1).

The cross section for excitation of the OVIII electron is (Bates and Griffing, 1953)

$$\sigma_{ex} = \frac{8\pi a_0^2}{S^2} \int_{t_{min}}^{\infty} |F|^2 t^{-3} \left[1 - \frac{16}{(4+t^2)^2}\right]^2 dt \quad (4)$$

where F is the transition matrix element, $S^2 = m_0 V_p^2/2I_H$ (m_0 is the electron mass, Vp the velocity of relative motion, and I_H is the ionization potential of hydrogen) and $t_{min} = \frac{\Delta E}{2S}\left(1 + \frac{m\,\Delta E}{4MS}\right)$, with ΔE the energy of the Kα X-ray and M the reduced mass. The largest cross section occurs for the 1s-2p transition, for which

$$|F| = 2^{15/2} \frac{3t}{Z} \Big/ \left[4\left(\frac{t}{Z}\right)^2 + 9\right]^3 \quad (5)$$

where Z is the atomic number of oxygen in this case. In both charge exchange and excitation, the radiative decay time is small compared to the time between collisions.

IV. Kα X-Ray Flux

The equilibrium charge fractions (see appendix) can be used in conjunction with the above cross sections to determine the Kα X-ray yields from oxygen ions. Tables 1 and 2 show the dependence of this yield on, respectively, the components of the interstellar medium and the oxygen nucleus energy. This yield is expressed in terms of two multiplicities, viz:

$$M_8 = \left(\frac{n_z}{n_H}\right) \int_{E_i}^{E_f} v \left(\frac{n_H}{dE/dt}\right) \left[F_8 \sigma^z_{87} + F_7 \sigma_{ex}\right] dE \qquad (6a)$$

and

$$M_7 = \left(\frac{n_z}{n_H}\right) \int_{E_i}^{E_f} v \left(\frac{n_H}{dE/dt}\right) F_7 \sigma^z_{76} \; dE \qquad (6b)$$

where M_8 is the number of 0.65 keV (OVIII) photons and M_7 is the number of 0.56 keV(OVII) photons produced per oxygen nucleus as it loses energy from E_i to E_f, by scattering from a medium of atomic number Z. In equation (6), $(\frac{n_Z}{n_H})$ is the atomic abundance (atomic number Z) relative to hydrogen (Cameron, 1973), dE/dt is taken from equation (2), and F_i are the fractions of oxygen ions with charge i. As shown in Table 1, greater than 99% of the Kα X-rays come from scattering by interstellar hydrogen, helium, carbon, and oxygen, with hydrogen and helium being the most effective components. Table 2 shows a strong peak in yield around 1-2 MeV/nucleon oxygen for both lines.

Values of the Kα X-ray flux were calculated with several different candidate interstellar oxygen spectra. First we considered three theoretically

TABLE 1
MULTIPLICITY OF Kα X-RAYS-I

COMPONENT OF INTERSTELLAR MEDIUM	NUMBER OF Kα X-RAYS FROM EACH COMPONENT		
	O VIII LINE	O VII LINE	TOTAL
HYDROGEN	21.91	18.34	40.25
HELIUM	14.85	26.72	41.57
CARBON	1.83	1.03	2.86
NITROGEN	0.60	0.24	0.84
OXYGEN	3.12	0.84	3.96
TOTAL $Z \leq 30$	42.75	47.21	89.96

TABLE 2

MULTIPLICITY OF Kα X-RAYS-II

OXYGEN ENERGY INTERVAL (MeV/Nucleon)	MEAN VELOCITY ($\overline{v}$/c)	NUMBER OF O VIII PHOTONS	NUMBER OF O VII PHOTONS
10 – 9	0.143	0.13	–
9 – 8	0.135	0.20	–
8 – 7	0.127	0.31	–
7 – 6	0.118	0.52	–
6 – 5	0.109	0.96	–
5 – 4	0.098	1.97	0.01
4 – 3	0.087	4.87	0.12
3 – 2	0.073	14.67	2.49
2 – 1	0.057	18.75	33.50
1 – 0.9	0.045	0.23	5.71
0.9 – 0.8	0.043	0.10	3.51
0.8 – 0.7	0.040	0.03	1.63
0.7 – 0.6	0.037	0.01	0.21
0.6 – 0.5	0.035	–	0.03
	TOTALS	42.75	47.21

constructed spectra called W, R, and T, where W refers to a power law source spectrum in total energy, R in rigidity, and T in kinetic energy per nucleon. Each of these has a power law index of -2.6 and is normalized to the observed relativistic oxygen spectrum, which is known to represent a galactic component (Balasubrahmanyan and Ormes, 1973). The interstellar spectra corresponding to these idealized source spectra were obtained by evaluating the modification arising from propagation through an interstellar medium approximated by an exponential distribution of path lengths with a mean path length of 4.5 gm/cm^2. (cf, Cowsik et al., 1967). They are presented to bracket order of magnitude effects and not to reproduce the details of the interstellar spectrum which is solar modulated to give the observed subrelativistic spectrum.

The oxygen spectrum observed near the earth was also used as a candidate interstellar spectrum (Hovestadt et al., 1973, McDonald et al., 1974), and is called A. This spectrum contains a remarkably high flattened out region between 1-30 MeV/nucleon observed during different phases of the solar cycle and could represent an anomalous component of the interstellar cosmic ray oxygen spectrum.

Lastly, a theoretical interstellar spectrum constructed to produce the subrelativistic portion of the observed spectrum via a model of solar modulation was used (Fisk, 1974) and is called F.

The Kα X-ray intensity (photons m^{-2}sec^{-1}ster^{-1}) arising from a given oxygen spectrum is the sum of two components, I_8 (the 0.65 keV line intensity) and I_7 (the 0.56 keV line intensity). They are given by

$$I_8 = \Lambda_8\left(1-e^{-N_H/\Lambda_8}\right)\sum_z\left[\left(\frac{n_z}{n_H}\right)\int_{E_1}^{E_2}\left(F_8\sigma^z_{87}+F_7\,\sigma_{ex}\right)\frac{dJ}{dE}dE\right] \quad (7a)$$

$$I_7 = \Lambda_7\left(1-e^{-N_H/\Lambda_7}\right)\sum_z\left[\left(\frac{n_z}{n_H}\right)\int_{E_1}^{E_2}F_7\,\sigma^z_{76}\;\frac{dJ}{dE}dE\right] \quad (7b)$$

where Λ_8 and Λ_7 are the hydrogen columnar densities corresponding to unit optical depth at the respective spectral line energies, N_H is the hydrogen columnar density in the observing direction, $\frac{dJ}{dE}$ is the oxygen intensity spectrum, and other quantities are as before. The integral is not sensitive to the values of the limits E_1 and E_2 as long as they are sufficiently far from the peak range of 1-2 MeV/nucleon (See Table 2). We chose E_1 = 80 MeV/nuc and E_2 = 0.5 MeV/nuc. For the case of spectrum A, the oxygen flux below 1 MeV/nucleon was not used since it is presumably of solar origin.

The results of the line intensity calculations for low galactic latitudes ($N_H \gg \Lambda$) are shown in Table 3. Also exhibited there are the weighted line widths for both lines due to the Doppler broadening corresponding to each assumed spectrum. These are evaluated using the following expression:

$$W = \sum_{\Delta E_i} I(\Delta E_i) \frac{2V_i}{c} \Big/ \sum_{\Delta E_i} I(\Delta E_i) \tag{8}$$

where W is the weighted line width, $I(\Delta E_i)$ is the line intensity from the oxygen energy interval centered at E_i (kinetic energy per nucleon) and V_i is the ion velocity corresponding to E_i. The oxygen energy intervals are small compared to the energy range.

V. Discussion

Several investigators have observed the diffuse soft X-ray background in the spectral region considered here (Henry et al., 1971, Bunner et al., 1969, 1973, Davidsen et al., 1972). All report values $\leq$ 60 photons/ cm^2-sec-ster-keV for the intensity around 0.6 keV. The values of broadened line intensity resulting from the various trial oxygen spectra are listed in Table 3 who they are compared with this upper limit to the diffuse background. To obtain an approximate value for the spectral density of the lines, the line intensity is divided by the line width.

TABLE 3
Kα X-RAY LINE INTENSITIES

SPECTRUM	O VIII LINE			O VII LINE			FRACTION OF DIFFUSE BACKGROUND AT~0.6 KeV
	LINE INTENSITY (PHOTONS/ M^2-sec-STER)	LINE WIDTH (KeV)	SPECTRAL DENSITY (PHOTONS/ M^2-sec-STER-KeV)	LINE INTENSITY (PHOTONS/ M^2-sec-STER)	LINE WIDTH (KeV)	SPECTRAL DENSITY (PHOTONS/ M^2-sec-STER-KeV)	
W	0.17	0.090	1.89	0.15	0.062	2.42	7.2×10^{-6}
R	3.09	0.090	34.3	3.55	0.062	57.3	1.5×10^{-4}
T	339	0.090	3770	316	0.062	5100	1.5×10^{-2}
A	26.7	0.086	310	28.7	0.061	470	1.3×10^{-3}
F	318	0.088	3610	328	0.0585	5610	1.5×10^{-2}

If the A oxygen spectrum as observed is the solar modulated interstellar spectrum, then an upper limit to the magnitude of this modulation may be obtained. The corresponding maximum modulation factor for such subrelativistic cosmic ray oxygen is about 10^3. Otherwise, the line feature would exceed the total diffuse background at this energy. However, present X-ray observations cannot rule out a broadened line at $\sim$ 0.6 keV of intensity comparable to the background (cf., deKorte, 1973).

The F interstellar oxygen spectrum is the result of a model for solar modulation which attempts to account for the anomalous observed flux. This spectrum would produce a broadened line intensity which is about 1.5% of the total diffuse background at $\sim$ 0.6 keV. The steepest of the theoretical source spectra which match the relativistic interstellar oxygen spectrum, T(the power law in kinetic energy), yields a similar flux.

A charactersitic of this spectral feature which would favor low resolution detection is that the two oxygen emission lines at 0.65 and 0.56 keV are comparable in intensity and Doppler broadened to such an extent that they will overlap at $\sim$0.6 keV to form a broad enhanced spectral region extending over about 0.17keV. Therefore, a non-dispersive spectrometer with a spectral resolution $\leqslant$30% around 0.6 keV (e.g. a cooled Si(Li) solid state detector) could measure the true line to continuum ratio.

The galactic latitude dependence of this line intensity should also favor detection. For an interstellar hydrogen density $n_H \sim 1$ atom/cm^3, the distance corresponding to unit optical depth at 0.6 keV is $\sim$ 500 pc (Brown and Gould, 1970), which exceeds the scale height of gas in the galactic disk. Therefore, the line flux should linearly track the hydrogen columnar density at high galactic latitudes (e.g. at $|b| \gtrsim 20°$). Furthermore, since the overall diffuse background tends to decrease with latitude (cf., Bunner et al.

1971), the feature would become more visible at low latitudes.

VI. Summary

If the flux of low energy cosmic ray oxygen is sufficiently large, K_α X-ray line emission from these nuclei will comprise a significant fraction of the total diffuse flux at $\sim$0.6 keV. A satellite borne detector with resolution $\leq$30% could observe this feature if the subrelativistic interstellar cosmic ray oxygen spectrum is as large as certain theoretical estimates make it, as discussed in the text.

We would like to thank Dr. K. Omidvar, Dr. L. A. Fisk, Dr. P. J. Serlemitsos, and Dr. F. B. McDonald for helpful discussions on this work.

Appendix

Three calculational methods are used to determine the equilibrium charge fractions of the oxygen ions in the interstellar medium. The average oxygen charge determines the particle energy régimes wherein each method applies.

If F_i is the fraction of ions in the i charge state such that

$$\sum_i F_i = 1 \qquad (A1)$$

then the average charge is defined by

$$\bar{i} = \sum_i i F_i \; . \qquad (A2)$$

We can also define the rms dispersion of the charge distribution as

$$d = \sum_i \left[(\bar{i} - i)^2 F_i \right]^{\frac{1}{2}} . \qquad (A3)$$

In the range $1 \leq \bar{i} \leq 7$ the charge distribution is nearly gaussian (Nilolaev 1965, Betz 1972) and the charge fractions can be written:

$$F_i \simeq (2\pi d^2)^{-\frac{1}{2}} \exp\left[-(i-\bar{i})^2 / 2d^2 \right] . \qquad (A4)$$

The value of d is not sensitive to the atomic number of the medium or the ion velocity in the range $.025 < v/c < .067$ (Nikolaev, 1965). For this calculation $d = .7$. Also, $\bar{i}$ retains the same value to within 20% in different rarefied gases. Therefore, the average charge in the interstellar medium can be characterized to sufficient accuracy by the value for pure hydrogen.

From equation (A4), when $\bar{i} = 7$, $F_5 \sim .01$. The average charge of the oxygen ion increases with its velocity or energy. Hence, for oxygen energies greater than that corresponding to $\bar{i} = 7$, F_i is set equal to zero for all $i < 6$ and equation (A1) is modified to:

$$F_8 + F_7 + F_6 \simeq 1 \qquad (A5)$$

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This is energy region I, and the charge fractions are calculated in the following way:

Let $\sigma_{ii'}$ represent the cross section for an ion going from charge state i to charge state i'. Then for situations in which multiple electron losses and captures are much less probable than single losses and captures, we can write

$$F_i/F_{i-1} = \sigma_{i-1,i}/\sigma_{i,i-1} \; . \tag{A6}$$

Using this relation, the ratios F_8/F_7 and F_7/F_6 for oxygen nuclei in atomic hydrogen were calculated as a function of velocity. The capture cross section used is given by (Nikolaev, 1965)

$$\sigma_{i,i-1} \simeq \pi a_0^2 \, i^5 \, Z_{med} \, Z_{med}^{*5} \left(\frac{2V_0}{V}\right)^{12} \left[1 + 4 Z_{med}^* \frac{V_0^2}{V^2}\right]^{-4} \tag{A7}$$

where a_o is the Bohr radius, V_o the corresponding electron velocity, Z_{med} is the atomic number of the medium, and Z^*_{med} is the effective charge of the medium. For hydrogen $Z^*_{med} = Z_{med} = 1$.

The electron loss cross sections are extrapolated from calculations of the cross sections for loss of K electrons from hydrogenlike ions (Dmitriev et al., 1965) and heliumlike ions (Senashenko et al., 1968). The quantities σ_{78}/σ_{87} and σ_{67}/σ_{76} are plotted as functions of velocity in Figure 1, along with the best fit straight lines used as analytical expressions in the given velocity range.

From equation (A4) when $\bar{i} = 7$, $F_8 = F_6$. Using the results shown in Figure 1 the product $(F_8/F_7) \times (F_7/F_6) = 1$ when the ion energy is 1.58 MeV/nucleon. At energies larger than 1.58 MeV/nuc (region I) the cross section ratios and equation (A5) are used to determine the F_i.

In region II the gaussian nature of the distribution is employed to calculate $\bar{i}$ as a function of velocity from the known charge fraction ratios. These values of $\bar{i}$ are then substituted into equation (A4) to obtain absolute values for F_i. This region extends from $\bar{i} = 7$ down to $\bar{i} = 4.8$ below which value the average charge has been shown to be directly proportional to velocity for oxygen ions.

Nikolaev (1965) gives the following expression for $\bar{i}$, viz:

$$\bar{i} = k\, Z^{\frac{1}{2}}\, V/V_o \qquad \text{(A8)}$$

valid for a wide variety of ions and media, in the average charge range $.2Z<\bar{i}<.6Z$ where Z is the ion atomic number. The parameter k is a weak function of the atomic number of the medium (k = .4 in nitrogen, .38 in krypton, .35 in helium). For hydrogen k was calculated by setting $\bar{i} = 4.8$ in equation (A8) with V corresponding to the lower limit of region II. By this meth k = .327, which is consistent with the other values. In this average charge range, region III, equation (A8) is used to calculate $\bar{i}$, and equation (A4) i again used to calculate the F_i.

The calculated values for $\bar{i}$ and F_i are displayed in Figures 2 and 3 respectively. These results are consistent with the small amount of experimental information available in this velocity range (cf. Hubbard and Laver 1955), and compatible with Bohr's criterion that ions should be fully stripped of electrons at velocities $\geqslant Z\,V_o$.

Hydrogen is expected to be a very effective stripper at high velocities while not as effective as other gases at lower velocities (Betz 1972). The average charge would be expected to be somewhat higher in a solid medium. Heckman et al.. (1963) find charge fractions of oxygen nuclei in a solid comparable with those calculated in region I - the high velocity region.

In region III the average charge of the ions is indeed found to be lower than that observed in heavier gases (Hubbard and Lauer, 1955, Nikolaev et al., 1958).

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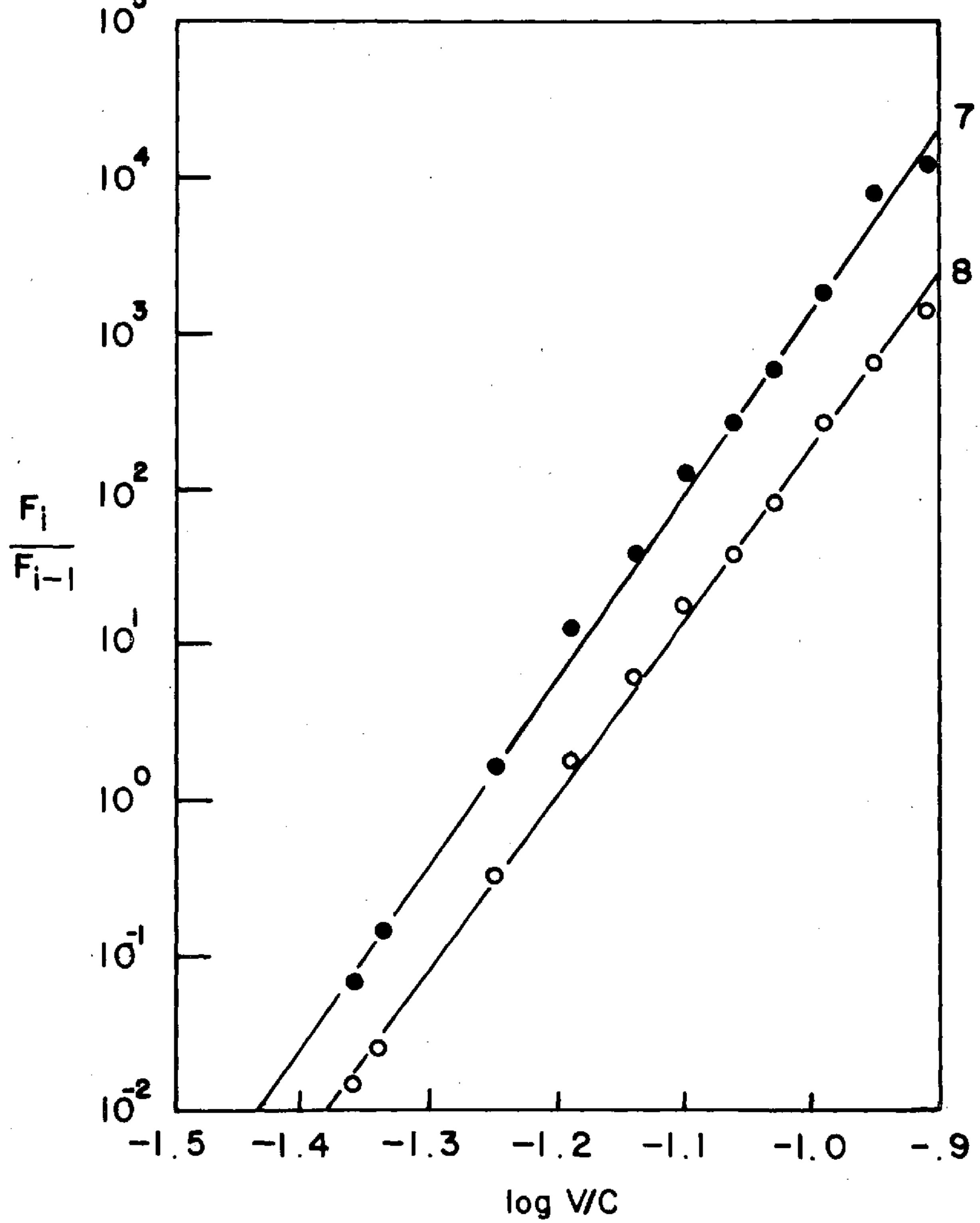
Figure Captions

Figure 1. The ratios of charge fractions of oxygen ions in hydrogen as functions of velocity. The straight lines correspond to best fits with correlation coefficients greater than .99. The values of i (charge) label each line.

Figure 2. The average charge of oxygen ions in hydrogen is shown as a function of velocity. Regions I, II and III refer to velocity ranges in which the different calculational forms described in the appendix are used.

Figure 3. The charge fractions of oxygen ions in hydrogen vs. velocity are plotted. Regions I, II and III are as in Figure 2. Values of i label each curve.

RATIO OF CHARGE FRACTIONS vs VELOCITY IN HYDROGEN



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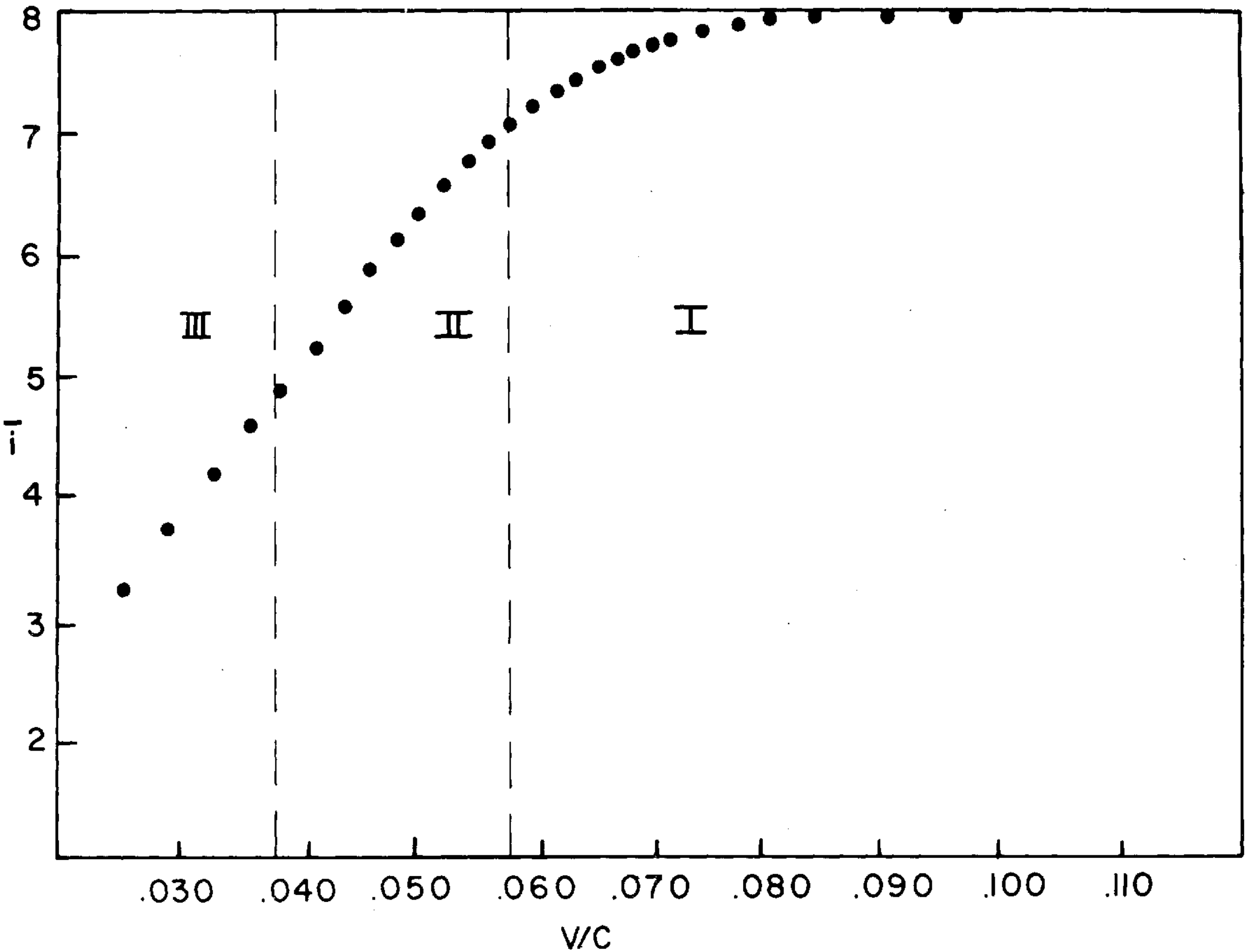

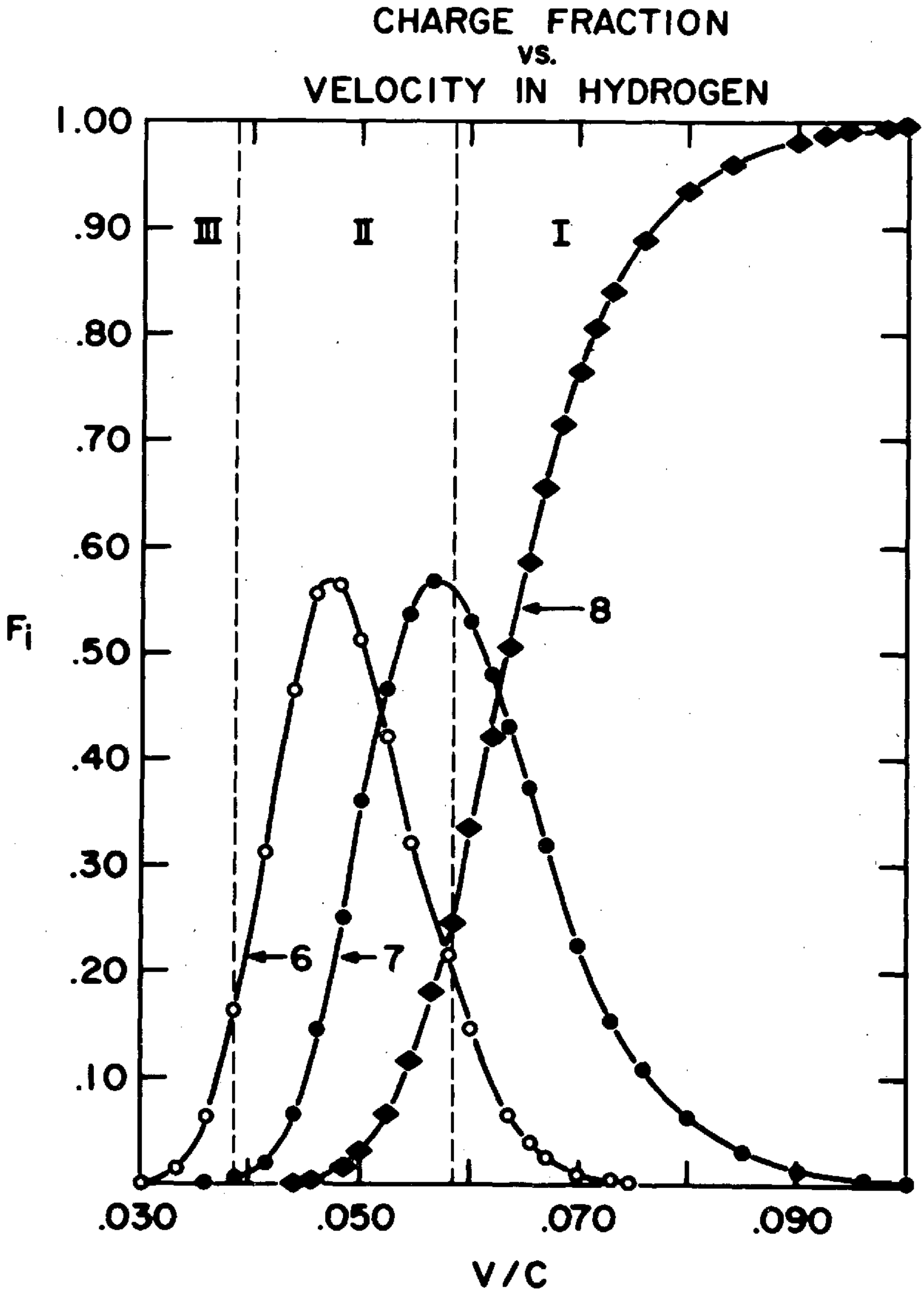
CHARGE FRACTION
VS.
VELOCITY IN HYDROGEN
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.80
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Fi
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