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G. A. Victor

John C. Raymond

Jane L. Fox, *Wright State University - Main Campus*

ELECTRON ENERGY LOSS IN OXYGEN PLASMAS

G. A. VICTOR AND JOHN C. RAYMOND

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

AND

J. L. FOX

Laboratory for Planetary Atmospheres Research and Department of Mechanical Engineering,
 State University of New York at Stony Brook, Stony Brook, NY 11794

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ABSTRACT

The results of calculations of the energy deposition of energetic electrons in oxygen plasmas are given. In a pure oxygen plasma even with large fractional ionization, much of the electron energy results in the production of additional ionization and excited electronic states. Results are given for separate calculations using theoretical and experimental cross sections for the important O I excitations of 1S and 1D because the theoretical and experimental data are not in agreement. These results are useful for understanding the spectra of oxygen-rich supernova remnants.

Subject headings: atomic processes — plasmas — supernova remnants

1. INTRODUCTION

Knots of oxygen with varying quantities of C, Ne, Mg, Si, and S, but not detectable H or He, have been found in the young supernova remnants Cas A (Kirshner & Chevalier 1977), G298 + 1.8 (Goss et al. 1979), N132D (Danziger & Deneffeld 1976; Lasker 1980), a supernova remnant in NGC 4449 (Blair, Kirshner, & Winkler 1983; Blair et al. 1984), 0540–69.3 (Mathewson et al. 1980), 1E 102.2–7219 (Dopita & Tuohy 1984; Blair et al. 1988; 1993), and Puppis A (Winkler & Kirshner 1985). The emission from these knots is generally attributed to heating by fairly slow shock waves (Itoh 1981, 1986; Dopita, Binette, & Tuohy 1984). However, Blair et al. (1986) and Blair, Raymond, & Long (1994) find that shock models fail to match the low-intensity ratios of ultraviolet to optical emission lines observed in 1E 102.2–7219 and N132D, and they attribute the optical and UV emission of those supernova remnants to photoionization and heating of the supernova ejecta by X-rays produced in the outer regions of the remnant. While it is possible that X-ray photoionization is much more important in these supernova remnants than in the others studied due to their exceptionally high X-ray luminosities and low densities, Dopita (1987) has pointed out that the models of radiative shocks encounter difficulties in explaining the observations of other supernova remnants. In particular, they fail to produce strong enough [O I] emission lines, and they would seem to require shock velocities in the unreasonably narrow range between 100 and 130 km s⁻¹ in all remnants to explain the [O III]/[O II] and [Ne V]/[Ne III] ratios. Dopita goes on to suggest that much stronger shocks in dense clumps of material produce strong X-ray emission, and that the optical and ultraviolet emission arises in the region where gas approaching the shock is ionized and heated by the X-rays.

Models of X-ray photoionized gas having the composition of material ejected by a supernova were computed by Blair et al. (1988), Dopita (1987), and Hamilton & Fesen (1988), but these models assumed that all the photon energy above the ionization potential of the absorbing ion went into heating the gas. It is well known, however, that in neutral gas nearly all the energy of the primary photoelectron goes directly into

atomic excitations or secondary ionizations, producing approximately one ion-electron pair for each 30 eV of energy. Shull & van Steenberg (1985) have computed the energy loss for fast electrons in gas dominated by hydrogen and helium, as is typical of most astrophysical plasmas. The excitation and ionization losses for a plasma of SN ejecta composition ought to be even larger, because singly ionized hydrogen is not susceptible to further ionization or excitation, while ions such as O⁺, O⁺⁺, and so on have large inelastic collision cross sections. Therefore, calculations of the ionization, excitation, and heating by fast electrons in oxygen-dominated gas in various states of ionization are needed to make realistic models of young supernova remnants and, for that matter, supernovae themselves (e.g., Begelman & Sarazin 1986).

Oxygen is the most abundant element in all the supernova remnants listed above, and the effects of various smaller amounts of carbon, neon, and other elements should be secondary. Therefore, we have computed the electron energy losses in pure oxygen gas using the methods of Fox & Victor (1988). The atomic data are described in § II, the calculation results are presented in § III, and a brief discussion of the implications of these results for the existing models is given in § IV.

2. ATOMIC DATA

The excitation cross sections for O II and O III were obtained from fits of the collision strengths to the form

$$\Omega = A + B/X + C/X^2 + D \ln X.$$

Ω is the collision strength and X is the energy in units of the appropriate excitation or ionization threshold energy.

For O III, the distorted wave calculations of Mann (1980) were used. These cover the full energy range we consider, and they agree well with the calculations by Bhatia, Kastner, & Behring (1982). The excitation of the singlet D metastable level was obtained from Mann's cross section increased near threshold to agree with the close-coupling calculations of Baluja, Burke, & Kingston (1981), which include the contribution of resonances. Fewer data are available for O II, especially at

higher energies. (Extensive R -matrix calculations unfortunately became available only after our calculations were completed; e.g., McLaughlin & Bell 1994). Cross sections were estimated by interpolating collision strengths of high and low Z ions of the Be-, B-, F-, and Ne-like isoelectronic sequences, then interpolating collision strengths for $2s-2p$, $2p-3s$, $2s-3p$, and $2p-3d$ transitions. This is clearly a crude approximation. The $2s-2p$ excitation rates are about a factor of 2 lower than those computed by Ormonde et al. (1973) at low energies.

The O II and O III ionization cross sections are taken from the tabulation of Arnaud & Rothenflug (1985). Excitation of the $K\alpha$ transition is assumed to lead to Auger ionization. The cross section was obtained by taking expressions from Lotz (1968) and using the Gaunt factor approximation of van Regemorter (1962). These K shell processes are not important.

For O I a much more detailed cross section data base is available largely due to the experimental program by Doering and co-workers, motivated by applications to aeronomy (Doering 1992a; Doering 1992b; Gulcicek & Doering 1988; Doering & Vaughan 1986; Doering & Gulcicek 1989; Doering, Gulcicek, & Vaughan 1985). We use these experimental cross sections for most excitations. For ionization the cross section of Brook, Harrison, & Smith (1978), with 4S , 2P , and 2D branching ratios from Dalgarno, Henry, & Stewart (1964) are employed. K shell excitation and ionization cross sections use approximations from Lotz (1968) and van Regemorter (1962). For electrons in the energy range of interest K shell processes make only a small contribution and only at the highest energies, in contrast with photon deposition at similar energies. Photons deposit all of their energy except at high energies where they Compton scatter, while electrons always scatter usually with small energy loss.

What cross section to use for the very important O I excitations of the red (6300 Å) and green (5577 Å) lines is a more difficult problem. Theory has converged, with the simplest and most complicated highly correlated results essentially in agreement (Pradhan & Saraph 1977; Lane et al. 1972; and many later papers). The recent measurements of Doering and coworkers (Doering 1992a, b; Doering & Gulcicek 1989) report larger values, by up to a factor of 2 in magnitude, in the important threshold region. The experimental and theoretical shape of the cross section curves with energy may also differ, but within the error bars of the measurements it is not yet clear. It is very important for many astrophysical and aeronomical applications that this possible discrepancy be resolved by additional experimental and theoretical studies. Because of the importance of the issue of the cross section for O I excitation of 6300 Å and 5577 Å radiation, we have carried out separate calculations using both cross sections. We have ignored possible cross section shape discrepancies and used as the "experimental" values the theoretical cross sections multiplied by 2.0 for 1D and 1.6 for 1S in order to see if the results scale simply. The results do not scale simply by the above factors so we did all the calculations using both the theoretical and experimental cross sections for 6300 Å and 5577 Å.

For O I we include 19 excitation channels and six ionization channels. For O II we include seven excitation and two ionization channels. For O III we include 10 excitation and two ionization channels.

3. CALCULATIONS AND RESULTS

The calculations have been carried out using the methods presented by Cravens, Victor, & Dalgarno (1975) for electrons

in H_2 and by Fox & Victor (1988) for electrons in N_2 . The calculations use a discrete energy loss method for excitations. For ionization processes involving valence electrons, secondary electrons and all higher generation electrons are included. For inner shell processes with higher generation electrons, the treatment is not so accurate but it is not important as the cross sections are small. The elastic fast electron–ambient electron interaction is included as a discrete energy loss process following the methods of Dalgarno & Lejeune (1971), which are accurate for the energy grids employed in the current calculations. The electron–electron cross section used is that of Swartz, Nisbet, & Green (1971). Superelastic processes are not included and are not important for most applications. The calculations have been carried out with energy grids with spacings of 1.0 and 5.0 eV. The results are identical to within a fraction of a percent, much less than the uncertainties of the input cross section data. A process with a small cross section that has not been included in the original deposition calculation can be included as a perturbation using our codes.

We present the results of a typical calculation in Tables 1–6. For this example we study the energy deposition of incident electrons from 1000 eV down as a function of fractional ionization. The results presented are for total deposition of the incident energy. The calculations can be easily carried out for any input atom, ion, and electron concentration and can be used interactively to study the astrophysical objects listed in §§ 1 and 4. For our trial calculations we study the role of fractional ionization, going from nearly neutral gas to highly ionized plasmas. Our calculations assume an electron temperature of 1000 K and equal concentrations of O II and O III. The results are insensitive to the electron temperature except for very small changes in the percentage of energy going to heat the ambient electrons. We do not tabulate the results for each of the 36 excitation channels and the 10 ionization channels included in the calculation. Rather, for each electron energy E , and electron to O I concentration ratio e/O , we tabulate the percentage of energy heating the ambient electrons H , the total number of ionizations produced from O I, q_1 , the total number of ionizations produced from O II, q_2 , and the total number of ionizations produced from O III, q_3 . Also tabulated is the total number of excitations of O I, e_1 , the total number of excitations of O II, e_2 , and the total number of excitations of O III, e_3 .

The production of O I(1D), [O I], and O II(2D), [O II] are tabulated because of their interest in intensity ratios. For small fractional ionization ratios, most of the production of [O II]

FIG. 1.—Electron heating and ionization produced by 1000 eV electrons as a function of $[e]/[O I]$.

TABLE 1
HEATING, IONIZATION, AND EXCITATION FOR $[e]/[O\ I] = 300$

E	e/O	H	$q1$	$q2$	$q3$	[O I]	[O II]	$e1$	$e2$	$e3$
102.5.....	300.	94.8	0.001	0.020	0.006	...	0.001	...	0.054	0.099
		94.8	0.001	0.020	0.006	...	0.001	...	0.054	0.100
152.5.....	300.	92.2	0.002	0.055	0.021	...	0.002	...	0.100	0.190
		92.1	0.002	0.055	0.021	...	0.002	...	0.100	0.190
202.5.....	300.	89.9	0.004	0.099	0.041	...	0.002	0.001	0.151	0.284
		90.4	0.004	0.099	0.041	...	0.002	0.001	0.151	0.285
302.5.....	300.	87.7	0.007	0.205	0.091	...	0.003	0.001	0.264	0.485
		88.0	0.007	0.206	0.091	...	0.003	0.001	0.265	0.486
402.5.....	300.	86.2	0.011	0.324	0.148	...	0.005	0.001	0.387	0.696
		86.4	0.011	0.324	0.148	...	0.005	0.001	0.388	0.697
502.5.....	300.	85.3	0.015	0.453	0.211	...	0.006	0.001	0.519	0.915
		85.3	0.015	0.453	0.211	...	0.006	0.002	0.519	0.915
602.5.....	300.	84.4	0.019	0.586	0.276	...	0.007	0.002	0.655	1.14
		84.4	0.019	0.586	0.276	...	0.007	0.002	0.655	1.14
702.5.....	300.	83.7	0.023	0.725	0.344	...	0.009	0.002	0.796	1.37
		83.7	0.023	0.725	0.344	...	0.009	0.002	0.796	1.37
802.5.....	300.	83.0	0.028	0.868	0.413	...	0.010	0.003	0.940	1.60
		83.0	0.028	0.868	0.413	...	0.010	0.003	0.940	1.60
902.5.....	300.	82.5	0.033	1.01	0.485	...	0.012	0.003	1.09	1.83
		82.5	0.033	1.01	0.485	...	0.012	0.003	1.09	1.83
997.5.....	300.	82.6	0.037	1.15	0.554	...	0.014	0.003	1.23	2.06
		82.6	0.037	1.15	0.554	...	0.014	0.004	1.23	2.06

comes from ionization of O I and not direct excitations of O II. The first row of each data set was obtained using the theoretical 1D and 1S cross sections and the second row used the experimental 1D and 1S cross sections.

In Figure 1 we plot the percentage of energy going into electron heat and the total ionization production rate as a function of fractional ionization. The results are for an initial electron energy of 1000 eV. The fraction of electron energy going to electron heat increases with increasing fractional ionization, but saturates at about 82%. The total ionization rate decreases with increasing fractional ionization, but it also saturates at a value near 2. Even in a plasma with very high fractional ionization the 1000 eV photoelectrons produce more electron-ion pairs than the original photon.

Our predictions for the fraction of energy going into heating the electrons and into ionization agree fairly well with the calculations of Kozma & Fransson (1992) who computed the energy deposition and nonthermal excitation due to gamma rays in supernova ejecta. Kozma & Fransson used the continuous slow down approximation and considered much higher densities and somewhat lower ionization states than we consider here. They considered mixtures of elements including iron group elements.

4. DISCUSSION

Several analyses of the emission from highly enriched gases have assumed ionization and energy deposition by fast particles or by soft X-ray ionization, which deposits the energy in

TABLE 2
HEATING, IONIZATION, AND EXCITATION FOR $[e]/[O\ I] = 30$

E	e/O	H	$q1$	$q2$	$q3$	[O I]	[O II]	$e1$	$e2$	$e3$
102.5.....	30.	94.7	0.010	0.020	0.006	...	0.005	0.002	0.054	0.099
		94.8	0.010	0.020	0.006	...	0.005	0.003	0.054	0.099
152.5.....	30.	91.8	0.022	0.055	0.021	...	0.008	0.004	0.099	0.189
		91.9	0.021	0.055	0.021	...	0.008	0.004	0.099	0.189
202.5.....	30.	89.6	0.036	0.098	0.041	...	0.013	0.005	0.150	0.282
		90.1	0.036	0.099	0.041	...	0.013	0.006	0.150	0.283
302.5.....	30.	87.5	0.068	0.203	0.090	...	0.024	0.009	0.262	0.481
		87.7	0.068	0.203	0.090	...	0.023	0.009	0.262	0.483
402.5.....	30.	85.9	0.105	0.321	0.147	...	0.036	0.012	0.384	0.689
		86.2	0.105	0.321	0.147	...	0.035	0.012	0.384	0.690
502.5.....	30.	85.0	0.145	0.447	0.208	...	0.049	0.016	0.513	0.906
		85.0	0.145	0.447	0.208	...	0.049	0.016	0.513	0.906
602.5.....	30.	84.1	0.187	0.579	0.272	...	0.063	0.019	0.647	1.13
		84.1	0.187	0.579	0.272	...	0.063	0.020	0.647	1.13
702.5.....	30.	83.4	0.230	0.715	0.339	...	0.077	0.23	0.786	1.35
		83.4	0.230	0.715	0.339	...	0.077	0.024	0.786	1.35
802.5.....	30.	82.7	0.274	0.855	0.407	...	0.093	0.026	0.927	1.58
		82.7	0.274	0.855	0.407	...	0.092	0.027	0.927	1.50
902.5.....	30.	82.1	0.321	0.995	0.477	...	0.106	0.031	1.07	1.81
		82.1	0.321	0.995	0.477	...	0.106	0.031	1.07	1.81
997.5.....	30.	82.1	0.366	1.13	0.544	...	0.121	0.034	1.21	2.03
		82.1	0.366	1.13	0.544	...	0.120	0.035	1.21	2.03

TABLE 3
HEATING, IONIZATION, AND EXCITATION FOR $[e]/[O\ I] = 3$

E	e/O	H	$q1$	$q2$	$q3$	[O I]	[O II]	$e1$	$e2$	$e3$
102.5.....	3.	93.2	0.093	0.019	0.006	0.003	0.033	0.022	0.052	0.096
	3.	93.1	0.092	0.019	0.006	0.006	0.032	0.026	0.052	0.096
152.5.....	3.	89.9	0.204	0.052	0.020	0.003	0.072	0.036	0.095	0.180
	3.	89.9	0.204	0.052	0.020	0.007	0.070	0.039	0.095	0.180
202.5.....	3.	87.6	0.333	0.092	0.038	0.004	0.115	0.050	0.141	0.265
	3.	87.9	0.333	0.092	0.038	0.007	0.114	0.054	0.141	0.266
302.5.....	3.	85.0	0.624	0.185	0.082	0.004	0.211	0.080	0.242	0.444
	3.	85.3	0.625	0.185	0.082	0.008	0.210	0.084	0.243	0.445
402.5.....	3.	83.3	0.948	0.288	0.131	0.004	0.316	0.111	0.350	0.629
	3.	83.7	0.950	0.289	0.132	0.009	0.313	0.116	0.351	0.631
502.5.....	3.	82.5	1.30	0.398	0.184	0.005	0.430	0.143	0.464	0.821
	3.	82.5	1.30	0.398	0.184	0.010	0.430	0.148	0.464	0.820
602.5.....	3.	81.7	1.66	0.511	0.240	0.005	0.548	0.176	0.582	1.01
	3.	81.7	1.66	0.511	0.240	0.011	0.548	0.182	0.582	1.01
702.5.....	3.	81.1	2.03	0.628	0.297	0.006	0.668	0.210	0.703	1.21
	3.	81.0	2.03	0.628	0.297	0.012	0.668	0.216	0.703	1.21
802.5.....	3.	80.0	2.40	0.743	0.352	0.006	0.788	0.242	0.821	1.40
	3.	79.9	2.40	0.743	0.352	0.013	0.788	0.248	0.821	1.40
902.5.....	3.	78.8	2.77	0.855	0.408	0.007	0.909	0.273	0.937	1.59
	3.	78.8	2.77	0.855	0.408	0.014	0.909	0.280	0.937	1.59
997.5.....	3.	78.6	3.14	0.964	0.462	0.007	1.03	0.304	1.05	1.77
	3.	78.6	3.14	0.964	0.462	0.015	1.03	0.312	1.05	1.77

the form of ~ 0.5 keV electrons created by photoionization and Auger ionization. All these analyses have assumed that the energy is efficiently thermalized in the gas. Detailed calculations will be needed to ascertain the effects of ionization and excitation losses on the observable spectral lines, but some general comments can be made.

Blair et al. (1988, 1993) constructed of supernova ejecta photoionized by soft X-rays in order to match the optical and ultraviolet spectra of the Small Magellanic Cloud supernova remnant 1E 102.2–7219 and N132D in the Large Magellanic Cloud. The photoionization models were preferred over shock models because of the very weak ultraviolet emission, and because the X-ray luminosities of the remnants are strong enough to account for the observed level of excitation. Models

were constructed for various gas densities. The lower density models had fairly high ionization states, and in those cases more than 90% of the energy deposited should in fact be thermalized. Thus those models will be little affected by proper calculation of ionization and excitation losses. The higher density, low-ionization models will be more drastically affected, however, because most of the energy deposited will go into ionizations and excitation of ultraviolet lines. This increase in ionization will mean that the lowest temperature models will be more highly ionized, and will therefore produce the O I recombination lines as much as 30 times more efficiently. The secondary ionizations will tend to increase the fraction of the gas in the O⁺ ionization state, strengthening the [O II] lines, but the temperature may be too low for this to

TABLE 4
HEATING, IONIZATION, AND EXCITATION FOR $[e]/[O\ I] = 0.3$

E	e/O	H	$q1$	$q2$	$q3$	[O I]	[O II]	$e1$	$e2$	$e3$
102.5.....	0.3	82.6	0.694	0.014	0.004	0.027	0.243	0.176	0.040	0.073
	0.3	81.6	0.688	0.014	0.004	0.053	0.239	0.202	0.039	0.073
152.5.....	0.3	77.9	1.35	0.034	0.013	0.032	0.467	0.262	0.065	0.123
	0.3	77.2	1.35	0.034	0.013	0.062	0.465	0.293	0.065	0.122
202.5.....	0.3	75.0	2.05	0.055	0.022	0.037	0.704	0.349	0.091	0.170
	0.3	74.9	2.05	0.055	0.022	0.073	0.704	0.388	0.091	0.171
302.5.....	0.3	71.8	3.49	0.100	0.044	0.047	1.18	0.524	0.144	0.264
	0.3	71.9	3.50	0.100	0.044	0.094	1.18	0.575	0.145	0.265
402.5.....	0.3	70.1	5.00	0.146	0.066	0.059	1.67	0.695	0.198	0.356
	0.3	70.5	5.03	0.158	0.066	0.118	1.68	0.764	0.199	0.359
502.5.....	0.3	70.0	6.62	0.195	0.088	0.073	2.20	0.882	0.255	0.453
	0.3	69.6	6.61	0.195	0.088	0.143	2.19	0.954	0.254	0.452
602.5.....	0.3	69.8	8.25	0.245	0.112	0.086	2.73	1.07	0.313	0.550
	0.3	69.4	8.24	0.244	0.112	1.70	2.73	1.16	0.312	0.549
702.5.....	0.3	69.3	9.85	0.294	0.136	0.089	3.25	1.25	0.370	0.645
	0.3	68.9	9.84	0.294	0.136	0.196	3.25	1.35	0.369	0.644
802.5.....	0.3	67.0	11.2	0.334	0.155	0.109	3.69	1.39	0.416	0.719
	0.3	66.7	11.2	0.334	0.155	0.216	3.68	1.50	0.415	0.718
902.5.....	0.3	64.8	12.4	0.370	0.172	0.119	4.10	1.52	0.458	0.787
	0.3	64.4	12.4	0.370	0.172	0.235	4.10	1.64	0.457	0.786
997.5.....	0.3	64.3	13.8	0.409	0.191	0.129	4.54	1.67	0.503	0.862
	0.3	64.0	13.8	0.409	0.191	0.256	4.53	1.80	0.502	0.860

TABLE 5
HEATING, IONIZATION, AND EXCITATION FOR $[e]/[O\text{ I}] = 0.03$

E	e/O	H	$q1$	$q2$	$q3$	[O I]	[O II]	$e1$	$e2$	$e3$
102.5.....	0.03	56.5	2.08	0.004	0.001	0.164	0.723	0.716	0.013	0.024
	0.03	53.7	2.03	0.004	0.001	0.307	0.704	0.846	0.013	0.024
152.5.....	0.03	53.3	3.42	0.008	0.003	0.219	1.18	0.993	0.019	0.036
	0.03	50.9	3.38	0.008	0.003	0.410	1.16	1.17	0.019	0.035
202.5.....	0.03	51.5	4.75	0.012	0.005	0.275	1.63	1.27	0.025	0.046
	0.03	49.9	4.72	0.011	0.005	0.523	1.62	1.52	0.025	0.046
302.5.....	0.03	49.7	7.40	0.019	0.008	0.388	2.51	1.83	0.037	0.068
	0.03	48.2	7.38	0.019	0.008	0.741	2.50	2.18	0.036	0.067
402.5.....	0.03	48.8	10.1	0.027	0.011	0.505	3.40	2.39	0.048	0.088
	0.03	47.8	10.1	0.027	0.012	0.973	3.41	2.87	0.049	0.088
502.5.....	0.03	49.3	13.0	0.034	0.015	0.639	4.35	3.01	0.062	0.111
	0.03	47.5	12.9	0.034	0.015	1.21	4.32	3.55	0.060	0.109
602.5.....	0.03	49.6	16.0	0.043	0.019	0.771	5.33	3.63	0.075	0.134
	0.03	47.8	15.8	0.042	0.019	1.45	5.29	4.28	0.073	0.131
702.5.....	0.03	49.3	18.7	0.050	0.022	0.893	6.25	4.21	0.087	0.155
	0.03	47.5	18.6	0.050	0.022	1.69	6.20	4.96	0.085	0.152
802.5.....	0.03	47.2	20.7	0.056	0.025	0.976	6.89	4.60	0.095	0.169
	0.03	45.5	20.5	0.055	0.025	1.84	6.84	5.42	0.094	0.166
902.5.....	0.03	45.4	22.6	0.061	0.027	1.06	7.51	4.97	0.103	0.182
	0.03	43.8	22.4	0.060	0.027	1.99	7.46	5.86	0.101	0.179
997.5.....	0.03	45.3	24.7	0.066	0.030	1.15	8.23	5.40	0.112	0.198
	0.03	43.6	24.6	0.066	0.030	2.17	8.17	6.38	0.110	0.195

increase the $[O\text{ II}]/[O\text{ III}]$ ratio significantly. The time-dependent ionization calculations become much less important, as the cloud gas will approach ionization equilibrium much more rapidly. This will probably resolve the difficulty in producing strong $[C\text{ II}]$ emission.

Dopita (1987) suggested that the optical emission from oxygen-rich supernova remnants is produced in ionization fronts ahead of fast, nonradiative reverse shock fronts. This suggestion was motivated by the inability of radiative shock models to produce strong enough $[O\text{ I}]$ emission. He implicitly assumed complete thermalization of the energy deposited by photoionization, and his models predicted adequate heating to match some line ratios. Our calculations suggest that in the mostly neutral gas the ratio of the ionization rate to the

heating rate is more than an order of magnitude larger than assumed by Dopita as a result of both the factor of 2 reduction in heating and the factor of 5–10 increase in ionization due to secondary ionizations. Therefore, the gas is much closer to ionization equilibrium than predicted by the models, and the $[O\text{ I}]$ emission will be greatly reduced.

Careful consideration of the ionization and excitation losses will also be needed in modeling the late-time spectra of Type Ib supernova (Filippenko & Sargent 1989). The oxygen-dominated gas is believed to be heated and ionized by the positrons and gamma rays emitted by ^{56}Co , and the resulting emission spectrum will depend on the fraction of the energy which is thermalized. Begelman & Sarazin (1986) have estimated the physical conditions in SN 1985f from several

TABLE 6
HEATING, IONIZATION, AND EXCITATION FOR $[e]/[O\text{ I}] = 0.003$

E	e/O	H	$q1$	$q2$	$q3$	[O I]	[O II]	$e1$	$e2$	$e3$
102.5.....	0.003	35.4	2.88	0.001	0.000	0.640	0.994	1.72	0.002	0.004
	0.003	31.3	2.75	0.000	0.000	1.03	0.948	2.02	0.002	0.004
152.5.....	0.003	33.7	4.50	0.001	0.000	0.899	1.55	2.40	0.003	0.006
	0.003	30.0	4.33	0.001	0.000	1.54	1.49	2.83	0.003	0.005
202.5.....	0.003	32.7	6.09	0.001	0.001	1.15	2.08	3.08	0.004	0.007
	0.003	29.6	5.96	0.001	0.001	1.89	2.04	3.71	0.004	0.007
302.5.....	0.003	31.8	9.29	0.002	0.001	1.67	3.14	4.45	0.006	0.011
	0.003	28.8	9.18	0.002	0.001	2.22	3.03	5.36	0.005	0.010
402.5.....	0.003	31.3	12.5	0.003	0.001	2.20	4.21	5.82	0.007	0.014
	0.003	28.7	12.4	0.003	0.001	3.63	4.17	7.07	0.007	0.013
502.5.....	0.003	31.7	16.0	0.004	0.002	2.79	5.37	7.37	0.009	0.017
	0.003	28.6	15.7	0.004	0.002	4.52	5.25	8.78	0.009	0.016
602.5.....	0.003	32.0	19.6	0.005	0.002	3.37	6.55	8.91	0.011	0.021
	0.003	28.8	19.2	0.005	0.002	5.47	6.40	10.6	0.010	0.020
702.5.....	0.003	31.9	22.9	0.006	0.002	3.19	7.65	10.3	0.013	0.024
	0.003	28.7	22.4	0.005	0.002	6.35	7.48	12.3	0.012	0.022
802.5.....	0.003	30.5	25.2	0.006	0.003	4.27	8.40	11.3	0.014	0.025
	0.003	27.5	24.6	0.006	0.003	6.93	8.21	13.4	0.013	0.024
902.5.....	0.003	29.3	27.4	0.007	0.003	4.62	9.12	12.2	0.015	0.029
	0.003	26.4	26.8	0.007	0.003	7.49	8.92	14.5	0.014	0.026
997.5.....	0.003	29.5	30.0	0.007	0.003	5.03	9.98	13.2	0.017	0.031
	0.003	26.6	29.3	0.007	0.003	8.14	9.76	15.8	0.016	0.029

emission-line ratios. Their analysis does not depend on the details of heating and ionization, though if only a fraction f of the energy deposited by radioactive cobalt is thermalized, their estimate of the initial mass of radioactive nickel must be increased by $1/f$. Our calculations cannot be applied directly, because the radiative lifetimes of the 1D and 1S levels are very

long so that collisions can depopulate the levels at the high densities observed in supernovae. Reasonable estimates could be made by assuming that the forbidden lines are in their high-density limits and that the excitation energy of the metastables goes into heating the electrons, but detailed model calculations are needed.

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