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THERMONUCLEAR BREAKUP REACTIONS OF LIGHT NUCLEI. II. GAMMA-RAY LINE PRODUCTION AND OTHER APPLICATIONS

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ABSTRACT

Various effects of the occurrence of nuclear breakup reactions in high temperature plasmas are considered. It is shown that the main consequence of these processes is to reduce the production of the gamma-ray lines (4.438 MeV line from $^{12}C^*$, 6.129 MeV line from $^{16}O^*$, and others), due to the breakup of these species at high temperature. Results of new calculations of the emissivities of all the relevant γ-ray lines are presented, taking the breakup processes into account. The magnitude of the breakup effect on the line emissivities depends strongly on the temperature, but more importantly on the plasma density and on the "available time" for the ion processes. It is shown that these dependences allow one, in principle, to determine these quantities from comparisons of the line emissivity measurements with the calculations.

The other main effect presented and treated here is the production of neutrons (from breakup of helium) and its consequences (gamma-rays from n-capture reactions, dynamical effects in accretion disk plasmas, and so forth). A minor effect concerning the differential breakup of the isotopes of each light element (and its consequence on the various isotopic abundances) is also briefly mentioned at the end.

Subject headings: gamma rays: general — nuclear reactions

I. INTRODUCTION

Nuclear breakup reactions, in which light nuclei are broken up by protons, alpha-particles, neutrons or photons were recently treated in substantial detail (Guessoum 1988; Guessoum and Gould, hereafter Paper I). The motivation for such work came out of the growing interest in so-called relativistic or high-temperature astrophysical plasmas, which are believed to occur in accretion disks surrounding compact objects and in central energy sources of active galactic nuclei and quasi-stellar objects. Except for a few recent treatments, most of the studies in this field have focused on the photon-electron-positron components of the plasmas and the processes taking place in such relativistic conditions (Guilbert and Stepney 1985; Dermer 1984; Zdziarski 1984; to cite a few). On the ion processes, Gould (1982) addressed the thermalization question and mentioned the breakup reactions, and then followed it with a treatment of the breakup of ^{4}He (1986). Aharonian and Sunyaev (1984, 1987) discussed the breakup (or spallation) of the light nuclei, and the production and capture of neutrons in such plasmas; Hogan and Applegate (1987) considered the possibility of inducing r-process nucleosynthesis in accretion disks by the neutrons produced in the breakup reactions; Guessoum and Dermer (1988, 1989) treated the processes (pair processes, nuclear reactions, energy losses and exchanges) occurring in a two-temperature H/He plasma, and the effects therein, namely, the gamma-ray line production, the production and capture of neutrons, and the variations of the abundances of light species.

The most extensive treatment of the thermonuclear breakup processes (reaction rates, conditions for occurrence for the various light species, and the effect on the plasma composition) was given in Paper I, to which the present paper constitutes the complementary part. In Paper I, which discusses processes and effects, we presented the different kinds of breakup reactions (which can be induced by protons, neutrons, or photons), compared their relative importance through a reaction rate formulation, and gave an account of the various physical quantities (threshold energy, Coulomb barrier, cross section, density, available time) which enter in such a treatment. Most importantly, the paper gave a simple and clear derivation of the temperatures needed for the breakup of the various species, and thus of the final plasma composition achieved with the ion temperature in different ranges. In that paper, as well as in the present one, thermal conditions are assumed. A simple calculation of the ion-thermalization time scale (Paper I) suggests that if the ion temperature is not too high, say below ~ 100 MeV, the ions will thermalize among themselves prior to undergoing breakup reactions. This question of ion-thermalization in hot plasmas will, however, be addressed in greater care and detail in a subsequent paper (Dermer and Guessoum 1989).

The present paper addresses a few important effects of the nuclear breakup reactions, namely, the reduction in gamma-ray line production and the various possible processes associated with neutron-production, and also some possible applications such as the determination of the ion-temperature and the density of the plasma, and the constraints that could be placed on the (poorly known) viscosity parameters of accretion disks. We will thus first present, in § II, the various processes responsible for the most important and relevant γ-ray lines investigated here, the formulation of the photon-emissivities of these lines (with and without the breakup effects), and the dependence of the emissivity functions on the plasma conditions and the breakup parameters: the ion temperature, the density, and the available time. At the end of that section, a suggestion will be made as to the possible determination of these quantities from comparisons of these calculations with (as yet unavailable) measurements. Section III will consider other possible effects/applications of the nuclear breakup phenomenon: n-production (and its effects), constraints on the viscosity parameters, compositional and spectral features ("unusual" and weak lines, line widths), and so forth.

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II. GAMMA-RAY LINE PRODUCTION: PROCESSES AND EMISSIVITIES

When the plasma temperature is high enough, protons and alphas can, in collisons with light nuclei (particularly "metals," i.e., C, N, O, Ne, and the like), bring these nuclei to excited states; these nuclei then emit characteristic gamma-rays upon deexciting to their ground states. For example, we may have

$$p + {}^{12}\mathrm{C} \rightarrow p' + {}^{12}\mathrm{C}^* , \tag{1}$$

followed by

$$ {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C}^{\mathrm{gs}} + \gamma(4.438 \text{ MeV}) . \tag{1a}$$

We may also observe characteristic gamma-ray lines from proton or neutron capture by light nuclei. We can thus have, for instance,

$$p + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma(5.494+ \text{ MeV}) , \tag{2}$$

or

$$n + \mathrm{H} \rightarrow {}^{2}\mathrm{H} + \gamma(2.224+ \text{ MeV}) . \tag{3}$$

We note here that (*a*) the intensities of such capture-lines will be much smaller (by several orders of magnitude) than those of the de-excitation lines (for comparison of the intensities of these lines, we plot their no-breakup emissivities in Fig. 1), as the processes (2) and (3) are partly electromagnetic; and (*b*) these capture-lines will be much wider (at the temperatures of interest here, i.e., $kT \gtrsim 1$ MeV) than the de-excitation-lines because the processes producing them (such as eqs. [2] and [3]) are nonresonant.

Such gamma-ray line processes were investigated in the past by several authors (Higdon and Lingenfelter 1977; Lingenfelter, Higdon, and Ramaty 1978; Ramaty, Lingenfelter, and Kozlovsky 1982), and calculations and curves of the photon emissivities (as functions of the temperature) have been published for plasma temperatures ranging from 10^8 to 10^{12} K. These calculations, however, did not take into account the breakup phenomenon, which, as was emphasized in Paper I, starts taking place at a temperature of $\sim$0.5 MeV (or 6×10^9 K). Indeed, at such temperatures, collisions between protons and light nuclei lead to a gradual spallation of the light species, thus to a smaller number of nuclei to be excited, and hence to a reduced gamma-ray line emissivity. In this section, we recalculate the emissivities of a few, important lines, reproducing and improving the accuracy of the no-breakup results, but more importantly showing that taking the breakup processes into account can have a drastic effect on these gamma-ray line emissivities.

a) *Gamma Lines from De-excitation of Nuclei*

The most investigated and well known of these deexcitation lines is the 4.438 MeV line produced by ^{12}C. The excited state can be reached through collisions of protons or alphas with carbon, nitrogen, or oxygen nuclei:

$$p + {}^{12}\mathrm{C} \rightarrow p' + {}^{12}\mathrm{C}^* , \tag{4a}$$

$$\alpha + {}^{12}\mathrm{C} \rightarrow \alpha' + {}^{12}\mathrm{C}^* , \tag{4b}$$

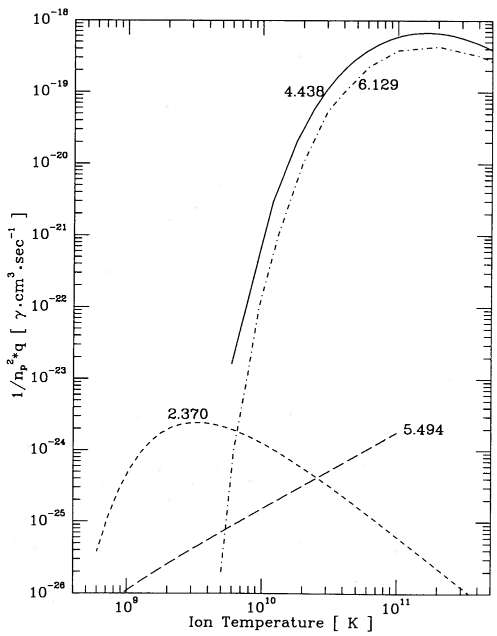

FIG. 1.—The emissivities $(1/n_p^2)(dN_\gamma/dV\,dt)$ of the main lines (when no breakup reactions are taken into account) are shown here against the ion temperature, for the purpose of comparing the relative importance of the lines. Note that the emissivities of the proton-capture (2.370 MeV and 5.494 MeV) lines are lower than those of the (4.438 MeV and 6.129 MeV) de-excitation lines by several orders of magnitude; see discussion in the text.

$$p + {}^{14}\mathrm{N} \to X + {}^{12}\mathrm{C}^* , \tag{4c}$$

$$\alpha + {}^{14}\mathrm{N} \to X + {}^{12}\mathrm{C}^* , \tag{4d}$$

$$p + {}^{16}\mathrm{O} \to X + {}^{12}\mathrm{C}^* , \tag{4e}$$

$$\alpha + {}^{16}\mathrm{O} \to X + {}^{12}\mathrm{C}^* . \tag{4f}$$

We note here that the first channel (4a) is often mistakenly thought of and identified as the sole process responsible for the production of ${}^{12}\mathrm{C}^*$, and hence of the 4.438 MeV line. In fact, that channel is sometimes not even the most effective process, as α-C collisions contribute dominantly at very high temperatures.

In the following treatment, we assume (as was done by the previously cited authors) that the plasma temperature is constant, i.e., that the plasma is in a steady state equilibrium situation. The emissivity quantity (number of photons emitted per unit time per unit volume) is simply given by the rate of production of ${}^{12}\mathrm{C}^*$ nuclei, which can be calculated using the equation

$$r = \sum_{ij} \frac{dN_{ij}}{dV\,dt} = \sum_{ij} \frac{1}{1 + \delta_{ij}} \iint \sigma_{ij}(v_{ij}) v_{ij}\, dn_i\, dn_j , \tag{5}$$

where i and j are the interacting particles in a particular channel, v_{ij} is their relative velocity, and σ_{ij} is the cross section for the production of ${}^{12}\mathrm{C}^*$ in the collision of i and j.

Rewriting (5) in terms of the kinetic energy available in the center of mass, we obtain the following expression for the emissivity function:

$$q = \sum_{ij} n_p^2 a_i a_j \left(\frac{8}{\pi \mu_{ij}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty dE_{ij} E_{ij} \sigma_{ij}(E_{ij}) e^{-E_{ij}/kT} , \tag{6}$$

where n_p is the proton density, a_i and a_j are the abundances of species i and j, $\mu_{ij} = m_i m_j/(m_i + m_j)$, σ_{ij} is the cross section for the particular channel.

In the previously cited studies of these lines, the abundances a_i were assumed to have solar values, and to be constant with time and temperature. However, at high temperatures, the breakup reactions significantly alter the various species abundances, so that these become functions of time, temperature, and density. We than have

$$a_i(t, n_p, T) = a_i^{(0)} \exp\left[-t/\tau_i(n_p, T)\right] , \tag{7}$$

where $\tau_i(n_p, T)$ is the breakup time scale or inverse of the breakup rate of species i (defined and calculated in Paper I), and $a_i^{(0)}$ is the abundance value at low temperature, which value can then be taken as solar.[2]

We thus obtain a corrected emissivity function $q(T, t, n_p)$:

$$q(T, t, n_p) = \sum_{ij} n_p^2 \left(\frac{8}{\pi \mu_{ij}}\right)^{1/2} a_i^{(0)} a_j^{(0)} e^{-t/\tau_i} e^{-t/\tau_j} \frac{1}{(kT)^{3/2}} \int_0^\infty dE_{ij} \sigma_{ij} E_{ij} dE_{ij} . \tag{8}$$

The cross sections needed for these calculations (cross sections of the excitation processes [4a]–[4f]) were taken from Ramaty *et al.* (1975, 1979), and references therein.

It is clear that the magnitude of the breakup effect on the line intensities (the reduction in emissivity) will be larger with the temperature, but also with the density and the available time. More precisely, q will depend exponentially on n_p and t ($q \propto e^{-tn_p f(T)}$) since the breakup time scale τ_i is inversely proportional to the density. Also, the value of the parameter tn_p will determine the temperature at which the breakup effect becomes apparent, as can be confirmed by Figures 2*a*, 3, 4, and 5. Figure 2*a* shows a plot of the different 4.438 MeV line emissivities (for different values of tn_p) against the uncorrected emissivity, as a function of the ion temperature T. The bumps in the emissivity curves come from the different contributions of the various channels producing excited nuclei, the various channels having different temperature dependences, and the interacting nuclei having different breakup temperatures.

One can carry this calculation a step further and calculate, as do Lingenfelter *et al.* (1978), the line emission efficiency for a two-temperature plasma. This quantity is defined as the ratio of the line luminosity to the total luminosity radiated by the plasma. In a two-temperature accretion disk, the electrons achieve much lower temperatures than the ions. One can therefore reasonably assume electron temperatures T_e of the order of 10^9 K, whereas the ion temperature T_i can be taken between 10^{10} and 10^{12} K. If we assume, for simplicity, that electron-proton and electron-electron bremsstrahlung are the only radiative mechanisms in the plasma (i.e., neglecting electron-positron bremsstrahlung and possible synchrotron radiation), then we may write

$$\dot{w}^{e-p}_{\mathrm{brems}} = \frac{dE^{e-p}_{\mathrm{brems}}}{dV\,dt} = n_e n_p c r_e^2 m_e c^2 \alpha \frac{32}{3} \left(\frac{2\theta_e}{\pi}\right)^{1/2} (1 + 1.781\theta_e^{1.34}) , \tag{9}$$

and

$$\dot{w}^{e-e}_{\mathrm{brems}} = \frac{dE^{e-e}_{\mathrm{brems}}}{dV\,dt} = n_e^2\, 18.04 c r_e^2 m_e c^2 \alpha \theta_e^{1/2} (1 + 1.1\theta_e + \theta_e^2 - 1.25\theta_e^{5/2}) , \tag{10}$$

[2] The values used for these abundances were taken from Hua (1986): $a^{(0)}(\mathrm{H}) = 1$, $a^{(0)}(\mathrm{He}) = 0.07$, $a^{(0)}({}^{12}\mathrm{C}) = 4.15 \times 10^{-4}$, $a^{(0)}({}^{14}\mathrm{N}) = 9.0 \times 10^{-5}$, and $a^{(0)}({}^{16}\mathrm{O}) = 6.92 \times 10^{-4}$, values which are slightly different from those used by Higdon and Lingenfelter (1977).

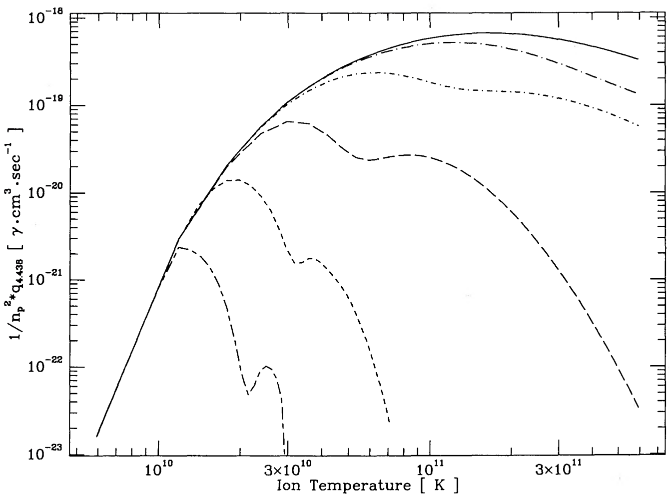

FIG. 2a

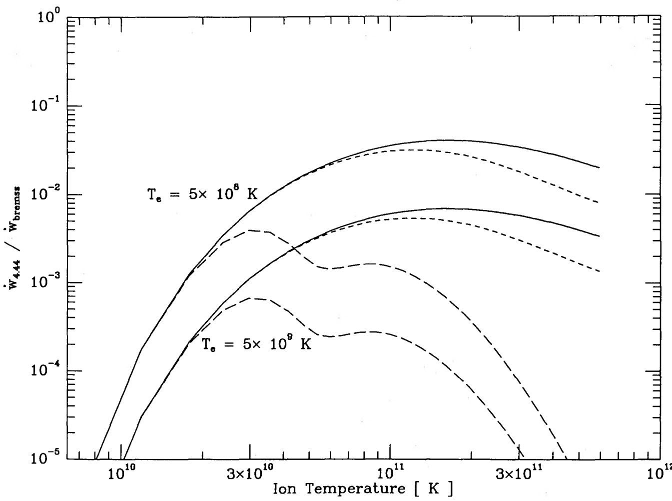

FIG. 2b

FIG. 2.—(a) The results of the calculation of the 4.438 MeV line emissivity, when breakup reactions are taken into account, are shown here for various values of the plasma parameter tn_p. The solid curve is the result obtained when no breakup is included; the dashed curves are, from top to bottom, for $tn_p = 3 \times 10^{14}$, 3×10^{15}, 3×10^{16}, 3×10^{17}, and 3×10^{18} cm^{-3}. (b) The 4.438 MeV line efficiency, that is, the line luminosity divided by the total luminosity (which is here assumed to be purely electron-proton and electron-electron bremsstrahlung), shown here against the ion temperature. The two sets of curves are for the two values considered for the electron temperature: $T_e = 5 \times 10^8$ and 5×10^9 K. The solid curves again show the no-breakup results, while the short-dashed and the long-dashed curves refer to the breakup results for $tn_p = 3 \times 10^{14}$, and 3×10^{16} s cm^{-3}, respectively.

when $\theta_e \equiv kT_e/m_e c^2$ is $\gtrsim 1$ (n_e and n_p are the electron and proton number densities, $r_e \equiv e^2/m_e c^2$ is the electron classical radius, and $\alpha \equiv e^2/\hbar c$).

The line luminosity can be written as

$$\dot{w}_{4.44} = \frac{dE_{4.44}}{dV\,dt} = E_{4.44} \times q_{4.44} \,. \tag{11}$$

In Figure 2b, we plot the line emission efficiencies versus the ion temperature T_i for two values of the electron temperature ($T_e = 10^9$ K and 5×10^8 K) in the two cases when the breakup processes are disregarded and when they are taken into account (with $tn_p = 3 \times 10^{15}$ s cm^{-3} and 3×10^{16} s cm^{-3}).

Several other de-excitation lines can similarly be treated. Their emissivities exhibit the same behavior as that of the 4.438 MeV line in the dependence on the ion temperature, and on the proton density and available time. It is nevertheless worth presenting some of the more important lines, with the new calculations.

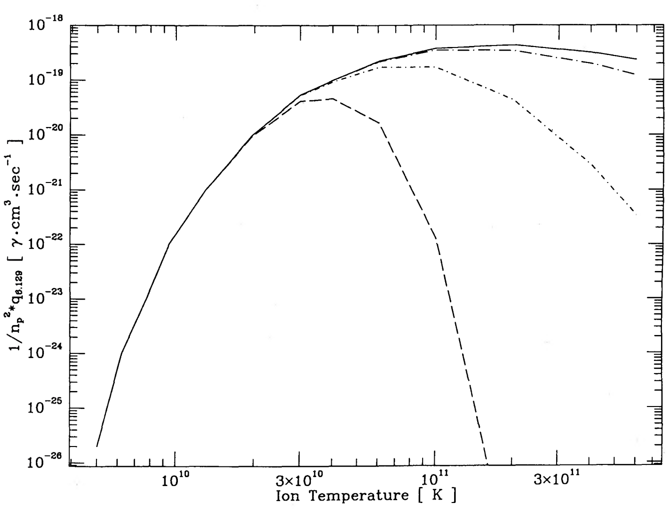

FIG. 3

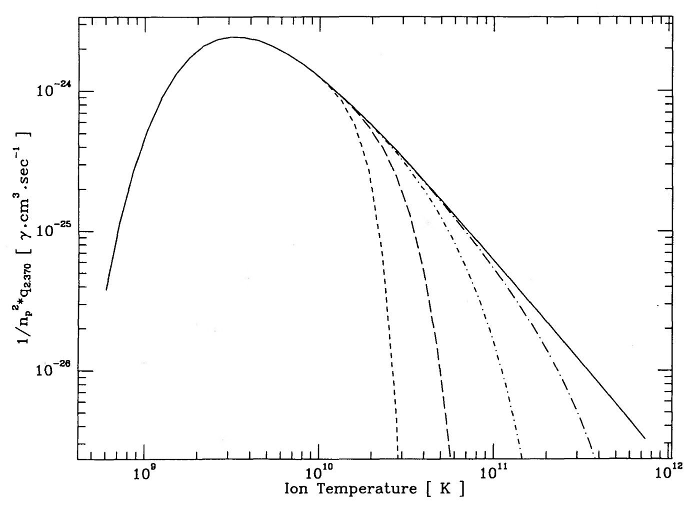

FIG. 4

FIG. 3.—The 6.129 MeV line emissivities are shown here against the ion temperature. The solid curve shows the no-breakup results; the dashed curves show the results obtained when the breakup reactions are included with $tn_p = 3 \times 10^{14}$, 3×10^{15}, and 3×10^{16} s cm^{-3}.

FIG. 4.—The 2.370 MeV line emissivities are shown here against the ion temperature. The solid curve shows the results one would obtain if the breakup reactions were not included; the dashed curves show the results obtained when the breakup reactions are taken into account with $tn_p = 3 \times 10^{14}$, 3×10^{15}, 3×10^{16}, and 3×10^{17} s cm^{-3}.

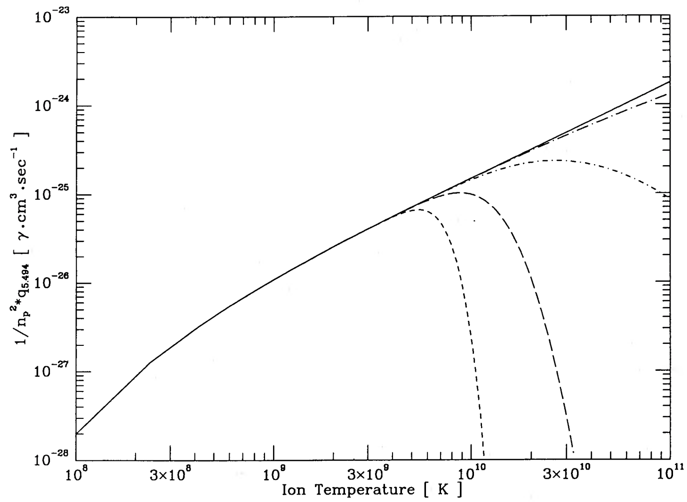

FIG. 5.—The 5.494 MeV line emissivities are shown here against the ion temperature. The solid curve shows the no-breakup results; the dashed curves show the results obtained when the breakup reactions are included with the parameter values $tn_p = 3 \times 10^{14}, 3 \times 10^{15}, 3 \times 10^{16}$, and 3×10^{17} s cm^{-3}.

Next to the 4.438 MeV line, the most important gamma-ray line is the one at 6.129 MeV, produced in the de-excitation of $^{16}O^*$. The main processes leading to the production of this line are

$$p + {}^{16}O \rightarrow p' + {}^{16}O^* , \tag{12a}$$

$$\alpha + {}^{16}O \rightarrow \alpha' + {}^{16}O^* , \tag{12b}$$

$$p + {}^{20}Ne \rightarrow X + {}^{16}O^* , \tag{12c}$$

and, to a lesser degree,

$$p + {}^{24}Mg \rightarrow X + {}^{16}O^* , \tag{12d}$$

$$\alpha + {}^{20}Ne \rightarrow X + {}^{16}O^* . \tag{12e}$$

The emissivity of this line at high temperature is shown in Figure 3., also with the breakup effects clearly displayed.

Next in importance are the 0.847 MeV and 1.634 MeV de-excitation lines from $^{56}Fe^*$ and $^{20}Ne^*$, respectively. The processes leading to these lines are

$$p + {}^{56}Fe \rightarrow p' + {}^{56}Fe^* , \tag{13a}$$

$$p + {}^{56}Fe \rightarrow n + {}^{56}Co , \tag{13b}$$

which is followed by

$$ {}^{56}Co \rightarrow {}^{56}Fe^* + e^+ + \nu ; \tag{13b'}$$

and, for the 1.634 MeV line,

$$p + {}^{20}Ne \rightarrow p' + {}^{20}Ne^* , \tag{14a}$$

$$p + {}^{20}Ne \rightarrow n + {}^{20}Na , \tag{14b}$$

which is followed by

$$ {}^{20}Na \rightarrow {}^{20}Ne^* + e^+ + \nu , \tag{14b'}$$

$$\alpha + {}^{20}Ne \rightarrow \alpha' + {}^{20}Ne^* , \tag{14c}$$

$$p + {}^{24}Mg \rightarrow X + {}^{20}Ne^* , \tag{14d}$$

$$p + {}^{28}Si \rightarrow X + {}^{20}Ne^* . \tag{14e}$$

And since we are here interested in these lines in the context of high-temperature plasmas ($T \gtrsim 10^{10}$ K, i.e., $kT \gtrsim 1$ MeV), we must note that due to the large velocities the nuclei have when they emit the photons, the (Doppler) line widths will be large. (For a 10 MeV plasma temperature, the 4.438 MeV line is ~ 100 keV wide!).

b) Gamma-Ray Lines from Proton-Capture

Another set of gamma-ray lines can be produced in the plasmas we are studying: they result from the radiative capture of a proton by a (light) nucleus. The most important of such lines is the one at 2.370 MeV, produced in the (resonant) capture of a proton by a ^{12}C nucleus:

$$p + {}^{12}C \rightarrow {}^{13}N + \gamma(2.370+ \text{ MeV}) . \tag{15}$$

In this process, for an energy larger than $E_{\rm th}^{\rm c.m.} = 0.457$ MeV, the ^{13}N nucleus is produced in its first excited state; it then de-excites to its ground state, emitting 2.370+ MeV photons.

One can also observe nonresonant radiative capture reactions such as

$$p + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + \gamma(5.494+\ \mathrm{MeV})\,. \tag{16}$$

In this process the ^{3}He nucleus is produced directly in its ground state.

These two kinds of p-capture reactions differ mainly in three ways:

1. The resonant reactions have nuclear thresholds (in addition to the Coulomb barriers the interacting nuclei must overcome), so that the production of photons necessitates a higher temperature "onset," but shows a steeper rise in the emissivity as a function of the temperature.
2. The resonant reactions have larger cross sections; hence the corresponding emissivities are larger in magnitude.
3. The spectra of the emitted photons are quite different in the two types of reactions: the nonresonant spectrum is much wider, as the width is then determined by the overlap of the (Maxwellian) distribution function and the cross section, whereas the width of the resonant spectrum is given by the thermal velocity of the ions; also, the peak of the nonresonant spectrum will be shifted by an amount approximately proportional to the temperature (proportional to $T^{2/3}$, to be more precise).

Again, the emissivities of these lines have been calculated in the past, by the same previously cited authors, for plasma temperatures of 10^8 to 10^{11} K. We redo these calculations, now including the breakup effects.

These lines are produced by only one process each, the process being induced by protons. The emissivity function can thus be written as

$$q_{pX}^{\rm cap} = n_p^2\, a_X \left(\frac{8}{\pi m_p}\right)^{1/2} \left(\frac{1 + A_X}{A_X}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty dE\sigma_{pX}^{\rm (cap)}(E) E e^{-E/kT}\,. \tag{17}$$

The rates of these capture reactions can be found in the review of Fowler, Caughlan, and Zimmerman (1975). Using these rates, we only need to introduce the breakup factor: $a_X \rightarrow a_X^{0} e^{-t/\tau_X(T)}$ [where $\tau_X(T)$ is the breakup time scale for species X, defined and calculated in Paper I], and recalculate the new emissivities for different values of the density and available time. Figures 4 and 5 show the results for the 2.370+ and the 5.494+ MeV lines. The importance of the breakup effects is again shown very clearly. It is thus clear from Figures 2–5, and this is one of the main points of this paper, that unless the parameter tn_p is very small ($\lesssim 10^{13}$ s cm^{-3}), the breakup processes will significantly reduce the gamma-line emissivities at high temperatures.

c) *Lines from Neutron Capture*

When the temperature and the density of the plasma are large enough, there can be substantial production of neutrons (which we treat in § III*c*); these neutrons can then be captured by light nuclei, yielding specific gamma-ray lines. The most important of those is of course the famous 2.224 MeV line from

$$n + p \rightarrow {}^2\mathrm{H} + \gamma(2.224+\ \mathrm{MeV})\,. \tag{18a}$$

Other such lines include

$$n + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + \gamma(20.578+\ \mathrm{MeV})\,, \tag{18b}$$
$$n + {}^2\mathrm{H} \rightarrow {}^3\mathrm{H} + \gamma(6.228+\ \mathrm{MeV})\,, \tag{18c}$$
$$n + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C} + \gamma(4.946+\ \mathrm{MeV})\,, \tag{18d}$$
$$\text{or} \qquad \rightarrow {}^{13}\mathrm{C} + \gamma(3.68\ \mathrm{MeV}) \qquad \text{(Resonant)}\,, \tag{18e}$$
$$n + {}^{14}\mathrm{N} \rightarrow {}^{15}\mathrm{N} + \gamma(10.83+\ \mathrm{MeV})\,, \tag{18f}$$
$$\text{or} \qquad \rightarrow {}^{15}\mathrm{N} + \gamma(5.6\ \mathrm{MeV}) \qquad \text{(Resonant)}\,, \tag{18g}$$

and so on.

Such lines are usually insignificant, as the neutrons are normally absent from the plasma. But at high temperatures ($kT \gtrsim 1$ MeV) neutrons become available again through the occurrence of the breakup reactions. However, the decay of the neutrons is a very critical process competing with the n-capture reactions. Let us compare the time scales for the processes: we have

$$t_{\rm decay} = 918\ \mathrm{s}\,, \tag{19}$$

$$t_{\rm cap} = \frac{1}{n_p \sigma_{np}^{\rm cap} v_n}\,, \tag{20a}$$

with

$$\sigma_{\rm cap}^{np} = \frac{7.32 \times 10^4 b}{v_n(\mathrm{cm\ s^{-1}})}\,, \tag{20b}$$

as quoted by Hua (1986), which gives

$$t_{\rm cap} = \frac{1.4 \times 10^{19}\ \mathrm{s}}{n_p(\mathrm{cm^{-3}})}\,. \tag{21}$$

Therefore n-p capture becomes significant only if the proton density is larger than $\simeq 1.5 \times 10^{16}$ cm^{-3}. When such is the case, the following equilibrium may take place in the plasma:

$$n + p \leftrightarrows d + \gamma \tag{22}$$

(Aharonian and Sunyaev 1984), which may lead to relatively large deuterium abundances. Aharonian and Sunyaev obtain ^{2}H-abundances of the order of 10^{-3} at temperatures around 3×10^{10} K.

The lines produced by n-capture reactions normally have very low intensities, partly because the cross sections of the associated processes are small (the processes being essentially electromagnetic), but mostly because the densities of the neutrons and the other light elements are quite small. Only the 2.224 MeV line production process is significant in that regard. Guessoum and Dermer (1988, 1989) have studied the relevance of this process in a hydrogen/helium accretion plasma at high temperature and considered the production of this line both inside the plasma and in the atmosphere of the companion of the compact object, after the neutrons escape from the accretion plasma and reach the star. That treatment gave 2.224 MeV line fluxes of 10^{-6} to 10^{-5} photons cm^{-2} s^{-1} in the case of the Cygnus X-1 system.

The other lines (processes [18b]–[18g]) may be of interest due to their relatively large energies.

III. APPLICATIONS OF THE BREAKUP REACTION CALCULATIONS

In this section, we consider other consequences of the nuclear breakup reactions on the composition, the spectrum, and the dynamics of the plasma, and possible applications of such effects.

a) *Determination of the Plasma Temperature and Density*

As can be seen from Figures 1–5, the emissivities of the gamma-ray lines we have been examining depend very strongly on the ion temperature, especially when the breakup reactions are taken into account. Therefore, a measurement of the emissivity allow one, in principle to determine the temperature. However, one obtains very different branches of the emissivity function for different values of the parameter tn_p, which is usually practically unknown. The reason it is practically unknown is because even if one can put limits on the proton density (from luminosities or other quantities), it is very difficult to determine the available time for the breakup processes, as that depends on many uncertain parameters such as the mass accretion rate, the mass of the compact object, the geometry of the accretion plasma, the strength of the magnetic field, and the viscosity conditions; it further depends on the energy exchange and loss mechanisms taking place in the plasma.

The emissivity plots also show that even when the parameter tn_p is too small to make the breakup reactions significantly alter the line-luminosity, the emissivity curve does not always provide a one-to-one determination of the temperature. Indeed, in some cases there can be two values of the temperature, both corresponding to the same value of q, the emissivity. Thus we can see that we need to combine different emissivity curves, in the hope of obtaining a unique emissivity-temperature curve that would be independent of any breakup effects (i.e., independent of tn_p). The best case would have been that the ratio $q(4.438)/q(6.129)$ be (even approximately) independent of tn_p, as these two lines have the largest emissivities and are therefore the easiest to observe. However, such is not the case, especially at $T \gtrsim 10^{11}$ K when breakup reactions affect the two lines very differently. One then needs to consider gamma-ray lines which are produced by the same nuclei, so that breakup effects do enter in exactly the same way and can therefore be eliminated by taking the ratio of the emissivities. And indeed, there are a few particular gamma-ray lines which present this characteristic. The problem with these lines (and it is a major one) is that their emissivities are very low, especially at intermediate-high temperatures ($T \approx 10^{10}$ K), because of the large threshold energies needed to produce them. If the temperature is much higher, however, their emissivities are much larger and there is a chance of observing such lines.

Let us give examples of processes and lines which present such characteristics. We have two lines produced in the de-excitation of ^{11}B*(2.124 MeV) and ^{11}C*(1.995 MeV) to their ground states, both excited nuclei being produced in collisions between protons and ^{12}C nuclei, i.e., in the reactions

$$p + {}^{12}\mathrm{C} \rightarrow p + p + {}^{11}\mathrm{B}^*(2.124\ \mathrm{MeV}) \tag{20}$$

$$p + {}^{12}\mathrm{C} \rightarrow n + p + {}^{11}\mathrm{C}^*(1.995\ \mathrm{MeV})\ . \tag{21}$$

We also have four other lines in the 6.3–6.8 MeV range, produced in the de-excitation of ^{11}C*(6.339 MeV), ^{11}C*(6.478 MeV), ^{11}B*(6.741 MeV), and ^{11}B*(6.791 MeV) to their respective ground states. The rates of production of these two groups of γ-ray lines can be calculated from the cross sections tabulated by Ramaty, Kozlovsky, and Lingenfelter (1979). And since all these γ-rays are produced in collisions between protons and ^{12}C nuclei, the breakup of carbon (at high temperatures) will affect the emissivities of these lines in exactly the same way it did for the 2.370 MeV line, produced in ^{12}C[p, γ(2.370)]^{13}N. We can thus take the ratios $q(2.370)/[q(1.995) + q(2.124)]$, and $q(2.370)/q(6.3\text{–}6.8)$, and these are then independent of tn_p. These ratios are plotted in Figure 6, and they show a strong dependence on the temperature. So these two quantities can allow a precise determination of T. The only inconvenience with the lines considered above is that their emissivities are still very low, even at high temperature. But there are, fortunately, a few other γ-ray lines which do not present this difficulty. We find four lines between 5.1 and 5.3 MeV, which are produced, as in the case of the 6.129 MeV line, almost solely by proton-oxygen reactions. These are the 5.180 MeV-line from ^{16}O(p, pn)^{15}O*(5.180), the 5.241 MeV line from ^{16}O(p, pn)^{15}O*(5.241), the 5.270 MeV line from ^{16}O(p, pp)^{15}N*(5.270), and the 5.298 MeV line from ^{16}O(p, pp)^{15}N*(5.298). So again the breakup reactions will affect each line emissivity in exactly the same way, and the ratios will also be independent of tn_p. Moreover, these lines present the advantage of requiring lower threshold energies, thus giving higher emissivities. The ratio $q(6.129)/q(5.1\text{–}5.3)$ is also plotted in Figure 6; it shows again a strong dependence on T, and varies over four orders of magnitude only, for $10^{10}\ \mathrm{K} \leq T \leq 10^{12}$ K, thus confirming that the latter group of lines has a fairly large emissivity. Clearly, this ratio is much better suited to determining the ion temperature, even though it is not absolutely exact, as α-O and p-Ne reactions have been neglected; the approximation, however, is very good.

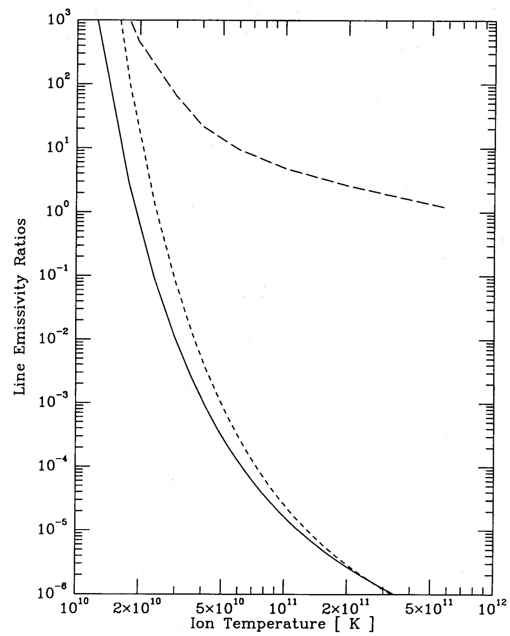

FIG. 6.—The ratios of line emissivities q, ratios which are independent of the breakup effects, are shown here against the ion temperature. The solid curve shows the ratio $q_{2.370}/(q_{1.995} + q_{2.124})$; the short-dahsed curve shows the ratio $q_{2.370}/q_{6.3-6.8}$ where 6.3–6.8 refers to the four lines at 6.339, 6.478, 6.741, and 6.791 MeV; the long-dashed curve shows the ratio $q_{6.129}/q_{5.1-5.3}$, where 5.1–5.3 refers to the four lines at 5.180, 5.241, 5.270, and 5.298 MeV.

Once the plasma temperature is obtained, one can go back to the $q(T, tn_p)$ curves and determine which tn_p value the emissivity measurement corresponds to. Knowledge of the value of tn_p can be highly important in distinguishing between various dynamical disk models (or flow conditions). Further assumptions will allow a determination of both the density n_p and the available time t (which is essentialy the viscosity time scale). At the very least, such emissivity measurements, combined with the calculations which take breakup reactions into account, can set important constraints on the viscosity parameters and models.

b) Neutron Production and Effects

The production of neutrons in high-temperature plasmas is a complicated problem, for it involves several processes, but it can be a very significant phenomenon and a valuable tool. If the temperature T is in the range T_d–T_α (where T_X is the temperature at which the X-species is broken up—see Paper I), all the neutrons come from the dissociation of ^{2}H, and the neutron density is then very low. If $T > T_\alpha$, the α-particles can be broken up to yield many more neutrons as the abundance of ^{4}He is much larger than that of ^{2}H.

The most important effect of this neutron-generation is the production of specific gamma rays through n-capture reactions, which were treated in § II*c*. However, there can be other consequences to this neutron-production. The neutrons can, of course, decay, which makes the time scales of the processes taking place in the plasma highly important; but more significantly, a fraction of the neutrons can escape and reach the companion star and again produce γ-rays (mostly the 2.224+ MeV line)—see Guessoum and Dermer (1988). And those neutrons which have not decayed or escaped[3] may provide the necessary viscosity to produce the outward transport of angular momentum in the accretion disk; this loss of angular momentum then leads to a gradual removal of the ions (from the plasma onto the compact star). Moreover, the neutron-proton coupling may also contribute to the energy dissipation (i.e., to the heating) in the plasma; this important effect will be treated in a subsequent paper (Guessoum and Kazanas 1989).

c) Other Effects: Rare Lines and Isotopic Composition

Another consequence of the occurrence of breakup reactions at high temperatures is the production of specific gamma-rays due to the creation of normally unabundant nuclei. For example, reactions between alpha-nuclei can lead to the production of ^{7}Li* and ^{7}Be*, which then de-excite and emit 0.478 and 0.431 MeV lines, respectively. These processes require threshold energies of about 18 MeV and can therefore occur appreciably only at very high temperatures. These particular lines were also treated (in more detail) by Guessoum and Dermer (1988, and 1989). Other gamma-ray lines may also be produced in high-temperature conditions, from the nuclei produced in the breakup of the light (C, N, O, Ne, and ^{24}Mg) elements. For example, we may have ^{14}N(p, pp)^{13}C, and the ^{13}C nuclei would then be excited to produce 3.684 MeV photons via $^{13}\mathrm{C}({}^{p}_{\alpha}, {}^{p'}_{\alpha'})^{13}\mathrm{C}^*$(3.864 MeV). Likewise, we may have ^{16}O(p, pp)$^{15}\mathrm{N}({}^{p}_{\alpha}, {}^{p'}_{\alpha'})^{15}\mathrm{N}^*$(5.3 MeV and 6.3 MeV), ^{24}Mg(p, X)$^{22}\mathrm{Ne}({}^{p}_{\alpha}, {}^{p'}_{\alpha'})^{22}\mathrm{Ne}^*$(1.275 MeV), ^{12}C($p$, p p)$^{11}\mathrm{B}({}^{p}_{\alpha}, {}^{p'}_{\alpha'})^{11}\mathrm{B}^*$(4.443 MeV), and ^{4}He($\alpha$, pn)^{6}Li*(3.561 MeV).

We may also observe unusual relative abundances in the isotopes of certain elements, because of their different breakup rates. For

[3] A substantial number of neutrons escape only if the temperature is large enough for their thermal velocities (combined with their flow velocities) to allow them to overcome the gravitational binding.

example, ^{6}Li is much more easily broken up at $T \gtrsim 10^9$ K than ^{7}Li. So the ratio of their abundances can be much smaller, at such temperatures, than the usual value of $\approx 10\%$ (as quoted by Gibson 1980). Similarly, ^{21}Ne and ^{22}Ne, which normally constitute 10% of all the neon nuclei, do not require a threshold energy for their breakup and can thus be destroyed at temperatures lower than 1 MeV, contrary to ^{20}Ne which can only be broken up at temperatures larger than ~ 1 MeV. Consequently, a plasma which has (or has gone through a stage with) a temperature in the neighborhood of 10^{10} K will probably have only those isotopes with the largest binding energy per nucleon (i.e., ^{7}Li, ^{12}C, ^{16}O, ^{20}Ne, and the like). Of course, such effects would be minor and difficult to confirm.

IV. SUMMARY

The principal effect of the nuclear breakup reactions is to deplete the species which normally participate in gamma-ray production processes. As a result, the emissivity of γ-ray lines (from de-excitation of, and p-capture by, light nuclei) are reduced at high temperature. The effect becomes stronger as the temperature gets higher, and when the quantity tn_p (available time for the occurrence of the nuclear reactions times the plasma ion density) is large. When tn_p is larger than $\approx 10^{18}$ s cm^{-3} and $T \gtrsim 10^{10}$ K, the effect is so strong that the isotopes (and therefore the lines) are practically inexistent.

The effect, however, can be useful in that it may allow for the determination of the important plasma parameters T, n_p, and $t_{\rm viscosity}$, from comparisons of measurements of certain line emissivities (or rather their ratios) with the calculations, which must, of course, include the breakup reactions.

Another consequence of the nuclear breakup reactions is the production of neutrons at high temperatures, mainly from proton-helium collisions. The neutrons can then play various important roles: they can be captured by light nuclei to yield specific gamma-rays (perhaps establish an equilibrium such as $n + p \leftrightarrows d + \gamma$ and thus produce relatively large ^{2}H-abundances, if the proton density is larger than $\approx 10^{16}$ cm^{-3}); they can escape from the plasma, reach the atmosphere of the compact object's companion star, and produce 2.224 MeV photons; or they can provide some of the viscosity needed in the energy dissipation and angular momentum transport inside the accretion disk.

Finally, we may expect two minor effects from the occurrence of the breakup reactions. The product-nuclei (such as ^{13}C, ^{11}B, ^{6}Li, and others) can be excited and thus produce characteristic gamma-rays; such lines would obviously have very low intensities, however. Also, we can expect that a plasma which has gone through a stage with a temperature in the range 10^9–10^{10} K (i.e., 0.1 to 1 MeV) to have only those isotopes which have highest binding energies per nucleon, for nuclei such as ^{6}Li, ^{15}N, and ^{18}O, even though they are stable, are much easier to break, at such temperatures, than their respective isotopes ^{7}Li, ^{14}N, ^{16}O, which require threshold energies and thus temperatures larger than ≈ 1 MeV.

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