THE EARLY EVOLUTION OF GIANT H II REGIONS FORMED BY SUPERNOVA EXPLOSIONS*

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Abstract

Brandt et al. (1971) have shown that consistency in the combined observations of the Gum Nebula requires a giant H II region, presumably formed by the Vela X supernova explosion. Morrison and Sartori (1969) had concluded on the basis of their He II fluorescence theory of type I supernovae, that a giant H II region would be formed as result of the UV burst. In this paper the evolution of such a region, which cools after an initial ionization, is discussed. This discussion is then applied to the Vela X and Tycho supernovae. Other giant H II regions might not in general be as easily detectable as the Vela X region. The Tycho region may just be detectable in the O[II], O[III] optical lines or as a "hole" in the 21-cm emission line profiles (the latter is already suggested in the data). These giant H II regions last appreciably longer than the continuum radio sources within them.

Introduction

In the fluorescence model of Morrison and Sartori (1969), only a small part of the total energy is emitted in the visible (the "bolometric correction" is about 8 magnitudes). Most of the total energy leaves the supernova neighborhood in the form of He II Lyman-alpha photons ($h\nu = 40.8$ eV). The estimated photon number is $\sim 10^{62}$, corresponding to a primary energy of $\sim 10^{52}$ erg. The mean free path of these photons at $n_H = 1$ cm^{-3} is a couple of parsecs. An H II region with a sharp boundary will be formed, its radius at $n_H = 1$ cm^{-3} being about 100 pc. In this model the ionization of the Gum Nebula is attributed to those UV photons; it follows that the initial temperature is fairly high, about 10^5 °K.

Once the H II region is formed it cools because there is no further radiation ionizing the gas, while it grows slowly in size, since the emission during cooling

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is predominantly beyond the Lyman limit of hydrogen. The ionization of the interstellar gas starts immediately after the explosion; other theories which attribute the ionization to cosmic rays (Ramaty et al. 1971), or to UV photons from the expanding shock wave (Tucker 1971), predict a delayed formation (the region is formed $\sim 10^4$ years after the initial explosion occurred). Recent supernovae, like Tycho, are critical in deciding if the supernova explosion produces an ionized region much later than the time of the explosion or not.

We will discuss the evolution of a gas, having the cosmic abundances of Aller (1961), that is initially ionized to a high temperature (above $\sim$ 20,000 °K) and then cools with no further heat input to keep the temperature more or less constant.* We emphasize that this time-dependent treatment applies to any case in which the gas cools after an initial ionization and a high initial temperature, no matter what gave rise to the initial ionization. However, the discussion will be restricted to the Morrison-Sartori theory, with appropriate general remarks made whenever needed.

Most of the ideas in this paper, particularly the discussion on Tycho, were developed in a previous paper, herein referred to as Paper I (Kafatos and Morrison 1971).

Non-Steady State Cooling

Cox and Tucker (1969) showed that in the temperature range 10^4 °K - 10^5 °K the cooling of a cosmic gas is mostly due to ions of the elements H, He, C, O. These ions, once collisionally excited from the ground state, relax back to the ground state by allowed radiative transitions ("ions" includes the neutral stage too).

In their "steady state" treatment, Cox and Tucker assumed that collisional ionizations balance recombinations (dielectronic and radiative). In this case the abundance ratio for any ion z of an element i is:

$$\frac{n_z^i}{n_{z+1}^i} = \frac{\alpha^{Di}_{z+1,\,z}(T) + \alpha^{Ri}_{z+1,\,z}(T)}{C^i_{z,\,z+1}(T)} = \frac{\alpha^i_{z+1,\,z}(T)}{C^i_{z,\,z+1}(T)} \tag{1}$$

* The heating of the galactic gas and cloud formation due to supernova explosions are discussed by McCray and Schwarz (1971). In the present paper the early evolution of Fossil Strömgren Spheres is discussed (the cooling is only followed down to 10^4 °K).

($C^i_{z,\,z+1}$ is the collisional ionization coefficient of ion z, while $\alpha^i_{z+1,\,z}$ is the total (dielectronic and radiative) recombination coefficient of ion z+1; note that this ratio is a function of T only.) Since the abundance of any ion is fixed by temperature, it follows that the radiative power loss is only a function of T*; as was mentioned above, in the range 10^4 °K - 10^5 °K this radiative power loss is mostly due to cooling resulting when ions that were collisionally excited from the ground state radiate back to the ground state by dipole emission.

On the other hand, if the gas cools with no heat input to keep the temperature more or less constant (as in the present case where after the initial sudden UV ionization there is no further heat or ionization input, other than collisions in the gas) the ionic abundances are found from the solution of the coupled system of equations:

$$\frac{dT}{dt} = -\Lambda(T, \ldots, n^i_z, \ldots) \tag{2}$$

All z, all i
$$\frac{dn^i_z}{dt} = -\alpha^i_z n^i_z n_e + \alpha^i_{z+1} n^i_{z+1} n_e - C^i_z n^i_z n_e + C^i_{z-1} n^i_{z-1} n_e$$

(where α^i_z, C^i_z refers to $\alpha^i_{z,\,z-1}$, $C^i_{z,\,z+1}$). Thermal expansion in system (2) is assumed negligible, <u>i.e.</u>: $n_T = n_e + n_H$ = const. The ionic abundances found from system (2) might be different than the Cox and Tucker abundances. This is particularly prominent in hydrogen. If $dT/dt = T/f(T)$ is the Cox and Tucker energy loss rate, then the total cooling time $t_c = \int f(T)\, dT/T$ to cool down to 15,000 °K is $t_c \sim 10^4/n_T$ years, if $T \sim 10^5$ °K initially. According to the steady state model, hydrogen is half-neutral at 15,000 °K. The time for half of hydrogen to recombine is about $10^5/n_T$ years, <u>i.e.</u>: it cools down to 15,000 °K before it recombines appreciably. We thus expect the collisionally induced hydrogen Lyman-alpha cooling, which in the steady state is peaked around 20,000 °K, to be appreciably reduced. In Paper I the approximation $\Lambda(T, \ldots, n^i_z, \ldots) = \Lambda(T) \propto T^{1.857}$ was used in system (2). This approximation makes the computing much easier, since one may solve the ionization equations of a particular atom, <u>e.g.</u>: oxygen, along with $dT/dt = -\Lambda(T)$, instead of the complete system involving

* The radiative power loss $dE/dt\,dV$ (erg cm^{-3} sec^{-1}) is related to dT/dt by: $dE/dt\,dV = (3/2)\,k\,(1+x)\,n_T\,dT/dt$, where $n_T = n_e + n_H$ and $x = n_e/n_T$. In the non-steady state case one has to be careful since $dx/dt \neq 0$.

all atoms. It was found that this approximation yields similar results to the exact solution of system (2), except below 20,000 °K. If the density $n_T = n_e + n_H$ is 1 cm^{-3}* the total time to cool from 10^5 °K to 10^4 °K is 1.2×10^4 years in this approximation.

System (2) was solved exactly by including the following ions of the atoms H, He, C, O: hydrogen, both stages; helium all three stages; carbon, the first five stages; oxygen, the first four stages (the other carbon and oxygen stages are not important unless the initial temperature is higher than 2×10^5 °K). The cooling due to the forbidden lines O[II] 3727, 3729Å and O[III] 5007, 4959Å was also included in Λ; above 10^4 °K these are the strongest forbidden lines of any ion (the infrared forbidden lines of the ions C II, N III, O IV, Ne II are important below 10^4 °K, while the O[I], N[I], N[II], Ne[III], Ne[IV], Ne[V] lines are not as strong as the O[II], O[III] lines). The O[II], O[III] cooling should be appreciable below ~ 30,000 °K. At higher temperatures this cooling is small compared to the allowed line cooling. Hydrogen Lyman-alpha is dominant below 20,000 °K along with the O[II], O[III] cooling. Carbon and helium are important up to ~ 8×10^4 °K, while oxygen is dominant above 8×10^4 °K. We should point out that the cooling equation when the predominant cooling agent is hydrogen is:

$$\frac{dU}{dt} = \frac{3}{2} k(1+x)\, n_T \frac{dT}{dt} + n_T \left(\frac{3}{2} kT + I_H\right) \frac{dx}{dt} = - \mathcal{L}^H_{La} - \mathcal{L}^H_{Rec} - \mathcal{L}_{fob}$$

where I_H is the I. P. of hydrogen,

$$\frac{dx}{dt} = - x^2\, \alpha^{RH}_{10}(T) + x(1-x)\, C^H_{01}(T)$$

and $\mathcal{L}^H_{La}$, $\mathcal{L}^H_{Rec}$, $\mathcal{L}_{fob}$ are the cooling coefficients due to collisional excitation of the n = 2 level, due to recombinations and due to oxygen forbidden line emission respectively (see also Defouw 1970). If the region is optically thick in the Lyman continuum, then recombinations to the ground state are not taken into account in the above equations (for neutral hydrogen density $n_H \sim 10^{-3}$ cm^{-3}, the mean free path at the Lyman threshold is ~ 50 pc).

It was found that the total time to cool from 10^5 °K down to 10^4 °K under various initial ionic abundances is about 2×10^4 years.

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* From here on we assume that $n_T = 1$ cm^{-3}. For other n_T, notice that the transformation $t' = (1/\lambda)\, t$, $n'_T = \lambda n_T$ leaves (2) unchanged.

In Fig. (1) the Cox and Tucker radiative power loss curve is shown along with the approximation $\Lambda(T) \propto T^{1.857}$. In Fig. (2) the exact cooling curve (initial relative ionic abundances $H^+ = 1$, $He^+ = 1$, $C^{++} = 1$, $O^{++} = 1$) calculated by solving system (2) is shown, along with the above mentioned approximation. It was shown that the exact cooling curve, found from (2), doesn't depend very much on the assumed initial abundances and that the behavior of the system is the same after about 10^3 years. This is because the cooling time and the dielectronic recombination time or collisional ionization time (whichever is shorter) of the dominant cooling agents are comparable at high temperatures; around 10^5 °K they all are a few hundred years. If one starts the cooling at lower temperatures (as low as 20,000 °K) the cooling curve might initially be quite different for various initial abundances; for example around 20,000 °K a 10 percent change in the initial abundance of H^+, or x, makes a big difference in the cooling curve, since the collisional Lyman-alpha cooling rate depends on 1 - x. However the cooling curve settles to curve A of Fig. 2 after a few thousand years. We therefore expect slight changes in the cooling curve depending on the temperature at which the cooling begins and on the initial abundances, but the overall shape of the curve should be the same after some time has elapsed.

In any case the relative ionic abundances are not the same as those expected from the steady state theory (e.g.: hydrogen is almost completely ionized, $x = n_e/n_T \sim 0.87$, at $T \sim 10^4$ °K while according to the steady state theory it should be mostly neutral etc.).

As expected the collisional hydrogen Lyman-alpha emission rate is appreciably reduced from the values expected under steady state conditions (by a factor of 10 around 2×10^4 °K). The emission rate of hydrogen Lyman-alpha under steady state conditions and non-steady state conditions as a function of T_e is shown in Fig. (3) (if recombinations balance ionizations this emission rate is mostly due to collisional excitation of the n = 2 level; in the time-dependent model, the Lyman-alpha emission rate from recombinations dominates the emission rate due to collisions only if $T \sim 10^4$ °K).

The time evolution of the oxygen ions (initial conditions as before) is shown in Fig. (4). What is interesting is that the O [II], O [III] forbidden lines compete with the hydrogen Lyman-alpha in the cooling. These forbidden lines are much stronger than the hydrogen Balmer lines; H-alpha begins to compete with O [II], O [III] only below 10^4 °K. The volume emission rates (erg cm^{-3} sec^{-1}) of the hydrogen Lyman-alpha line (due to collisions and recombinations) and the oxygen forbidden lines as a function of time are shown in Fig. (5). The temperature of the region is also shown. The initial conditions assumed were: relative ionic abundances $H^+ = 1$, $He^+ = 1$, $C^{++} = 1$, $O^{++} = 1$, $T = 10^5$ °K (for different initial conditions the exact values of the O [II], O [III] lines may vary but always, at least O [II], compete with the hydrogen Lyman-alpha).

In solving system (2) the hydrogenic radiative recombination coefficients of Seaton (1959) and the formula of Burgess (1965) for the dielectronic recombination coefficients were used. The collisional ionization coefficients were those of Cox and Tucker (1969).

Application to Gum Nebula and Tycho

Brandt et al. (1971), by combining the known emission measure, the dispersion measure of the pulsar in Vela X, the neutral hydrogen measure, and the optical extinction, reach the conclusion that a giant H II region of low density ($\langle n_e \rangle \sim 0.16$ cm^{-3}, R $\sim$ 400 pc) engulfs the Gum Nebula, while its edge is only about 60 pc away from the Sun. The filaments seem to have densities appreciably higher than the mean. Brandt et al. find the root mean square electron density to be about 1.28 cm^{-3}; this is based on the assumption that the mean emission measure is $\sim$1300 cm^{-3} pc. The Gum Nebula may be the composite of a large diffuse and not very bright region, which was formed by the supernova explosion, and a smaller denser region, which surrounds the stars γ^2 Vel and ζ Pup and which is probably kept ionized by those stars (e.g.: discussion by Bok 1971). Although the above mentioned value of the emission measure is questionable (as discussed during the present conference) it seems that there is appreciable concentration of the nebular matter in the weakest part of the nebula.

The age of the pulsar PSR 0833-45 (Reichley et al. 1970) is 1.1×10^4 years. If the nebula was ionized 1.1×10^4 years ago by a UV burst and the initial temperature was quite high ($\sim 10^5$ °K), as expected from the fluorescence theory of type I supernovae, the diffuse region should still be quite hot. In Table 1 the temperature of a diffuse region ($n_e \sim 0.1$ cm^{-3}) as well as that of denser regions ($n_e \sim 1$ cm^{-3}, which is more appropriate for the filaments) is given for various ages of the nebula, assuming that the initial temperature was $\sim 10^5$ °K. These temperatures are consistent with the high temperatures of Alexander et al. (1971). On the other hand, regions which are appreciably denser than 1 cm^{-3} would cool down fairly fast after the initial explosion and their present temperature ($\sim 10^4$ °K) would have to be attributed to sources other than the initial UV burst. This is the case for the very dense ($n_e \sim 300$ cm^{-3}) filaments near Vela X observed by Milne (1968a, b) and maybe the smaller, dense region around γ^2 Vel and ζ Pup. The former very dense filaments are probably excited by the remnant itself, while the latter region is probably excited by γ^2 Vel and ζ Pup. In any case the Gum Nebula is fairly rich in H II emission clouds, stars, filaments etc. and one shouldn't expect to attribute everything to the supernova.

Table I
Age and Corresponding Temperature Assuming an Initial Temperature of 10^5 °K

n_e (cm^{-3})	Age (years)	T_e (°K)
1	5,000 11,000 20,000	25,000 15,000 10,000
0.1	5,000 11,000 20,000	75,000 55,000 40,000

The estimated total number of electrons in the H II region is, according to Brandt et al. (1971), about 2×10^{62} at present. The region in cooling from 10^5 °K to its present T $\sim$ 50,000 °K, doubles its size, since the predominant radiation, when cooling, is beyond the hydrogen Lyman limit. This gives $\sim 10^{62}$* for the initial UV photon number in accordance with the Morrison-Sartori estimates.

The Vela X H II region is made easy to detect by a combination of fortunate circumstances, the most important being its relatively nearby location. As pointed out in Paper I (see also discussion by Sartori 1971), the essential difference between an ionized region produced by the UV photons of the fluorescence theory and other mechanisms (such as the cosmic rays of Ramaty et al. 1971), or the UV photons from the blast wave of Tucker (1971) is the time to form the region. The Gum Nebula could have been produced by any of the above mechanisms. However a recent supernova (not older than $\sim 10^3$ years) should have already formed its "Gum Nebula" if the UV-burst is produced in the initial explosion but not if the formation of the ionized region takes place after 10^4 years. The known galactic supernovae younger than 10^3 years are the following: SN 1054 (the Crab Nebula Supernova), SN 1006, SN 1572 (Tycho's Supernova), SN 1604 (Kepler's Supernova) and Cas A. Of these only Tycho and Kepler are definitely of type I; of the others the Crab might be a unique remnant, not much is known about SN 1006, and Cas A is probably of type II and furthermore it is heavily obscured by dust. Kepler is further away than Tycho. Therefore the best supernova to test whether an ionized region is formed right after the explosion or much later, is Tycho (the following discussion is similar to that in Paper I).

* The total mass changes by at most a factor of 4 in the recent work of Alexander et al. (1971).

The Tycho remnant is only 400 years old. We expect the H II region to be quite hot still. Menon and Williams (1966) determined a distance of 3.5 kpc to Tycho, from their 21-cm absorption line measurements and a density of $n_H \sim 0.1$ cm^{-3}, at a distance about 100 pc above the galactic plane. Minkowski (1964, 1968) uses the distance 5 kpc and interstellar absorption for the remnant of ~ 2.1 magnitudes. (There is still considerable uncertainty at present as to the correct value of distance, according to Williams 1971.) We present in Table II the expected surface brightness of the large H II region ($n_e = 1$, $0.1\ cm^{-3}$ and 10^{62} electrons), as well as denser, small clouds ($n_e = 10\ cm^{-3}$), in the O [II], O [III] lines for Tycho at present. A constant optical absorption of 2 magnitudes was assumed. We also show the expected* H-alpha surface brightness for the above regions and the observed surface brightness of some weak normal H II regions in H-alpha (see Pottasch 1965).

We conclude the following: If $n_e \sim 0.1\ cm^{-3}$ the H II region will not be seen in any optical lines. If $n_e \sim 1\ cm^{-3}$ it may be possible to detect it in the O[III] lines 5007, 4959 A. Finally, small clouds with $n_e \sim 10\ cm^{-3}$, $R \sim 10$ pc (which should lie within 40 pc from the supernova in order to become completely ionized) would probably be seen in the O [II], O [III] lines. No H-alpha, H-beta radiation is detectable, except for the denser clouds, i.e.: those regions will not show the characteristic H-alpha, H-beta radiation of an H II region. The R = 10 pc, $n_e = 10\ cm^{-3}$ clouds would have a free-free radio flux of 1.5 f.u. at 1,000 MHz (3 f.u. if d = 3.5 kpc) while the giant region ($R \sim 100$ pc, $n_e \sim 1\ cm^{-3}$) flux is 10 f.u. (if d = 3.5 kpc, 20 f.u.). The small cloud fluxes are too weak to be detected, while the giant H II region is so large that it may be hard to distinguish from the background or from other sources (the remnant itself has a flux of 40 f.u. at 1,400 MHz). A more promising test of the situation would be to see if there is a deficiency of 21-cm emission in the neighborhood of the supernova.

At the position of Tycho, the velocity gradient across the cloud will be a couple of km/sec, comparable to the Doppler broadening at 100 °K. Such a "hole" in 21-cm line profiles would be hard to detect, but not impossible. Williams and Weaver (Williams 1971) have perhaps detected the H II region around Tycho. Their survey indicates that there is no doubt that a 21-cm deficiency exists around Tycho but it is uncertain whether it has anything to do with the supernova. The feature they see shows for several km/sec either side on the -45.2 km/sec velocity map; its diameter is approximately 1.5°. Williams and Weaver see similar holes in places where there is no known supernova remnant. This might be partially explained by the following argument: once an H II region is formed it lasts 10^6 - 10^7 years (if $n_e \sim 0.1$ - $1\ cm^{-3}$) while the supernova remnant survives not longer than $\sim 10^5$ years (Milne 1970).

* As long as $x = n_e/(n_e + n_H)$ is close to the equilibrium value, the H-alpha emissivity is as calculated by Parker (1964) for collisional excitation; this was found to be the case for $T \gtrsim 30{,}000$ °K.

Table II

Expected Surface Brightness of Tycho Model Regions and Observed Brightness in H-alpha of Normal H II Regions

A. Tycho Model Regions:

n_e (cm^{-3}) (assumed)	R (pc)	T (°K)	Angular Radius (arc min)		Surface Brightness (erg cm^{-2} sec^{-1})		
	(expected)		d = 3.5 kpc	d = 5 kpc	$S_{[O\ III]}$	$S_{[O\ II]}$	$S_{H\alpha}$
1	95	80,000	94	66	3×10^{-4}	7×10^{-5}	8×10^{-7}
0.1	130*	10^5	127	90	5×10^{-6}	2×10^{-7}	7×10^{-9}
10	10	27,000	10	7	1.3×10^{-3}	2×10^{-3}	10^{-4}

B. Normal H II Regions:

Name	n_e (cm^{-3})	R (pc)	Observed Angular Radius (arc min)	Observed $S_{H\alpha}$ (erg cm^{-2} sec^{-1})
IC 405	28	3.2	16 (d = 0.7, 0.525 kpc)	5×10^{-4}
λ Ori	10	11	100 (d = 0.37, 0.4 kpc)	3×10^{-4}
NGC 7000	16	19	65 (d = 1, 1.13 kpc)	8×10^{-4}

* The light flash has only had time to travel 130 pc since the supernova occurred; the expected equilibrium radius is ~ 200 pc. The H II region would still be growing with the speed of light if the density were this low.

Therefore the H II region should be seen long after the remnant has disappeared, in the same way that most pulsars (with a lifetime of $\sim 10^7$ years, Hewish 1970) are not associated with observable remnants.

In concluding it seems appropriate that the following observations should be made to increase our knowledge about the Gum Nebula and supernovae in general:

Interstellar clouds near Tycho, if they indeed exist, should be observed at the O [II], O [III] wavelengths; a survey of the Gum Nebula at the same wavelengths should be made. A survey of Tycho in the radio (21-cm as well as in the recombination lines of helium as pointed out by Dupree 1971) should be conducted. Finally a survey for large H I "holes" around the galaxy should be conducted and a correlation of these with known supernova remnants or pulsars should be made.

Acknowledgments

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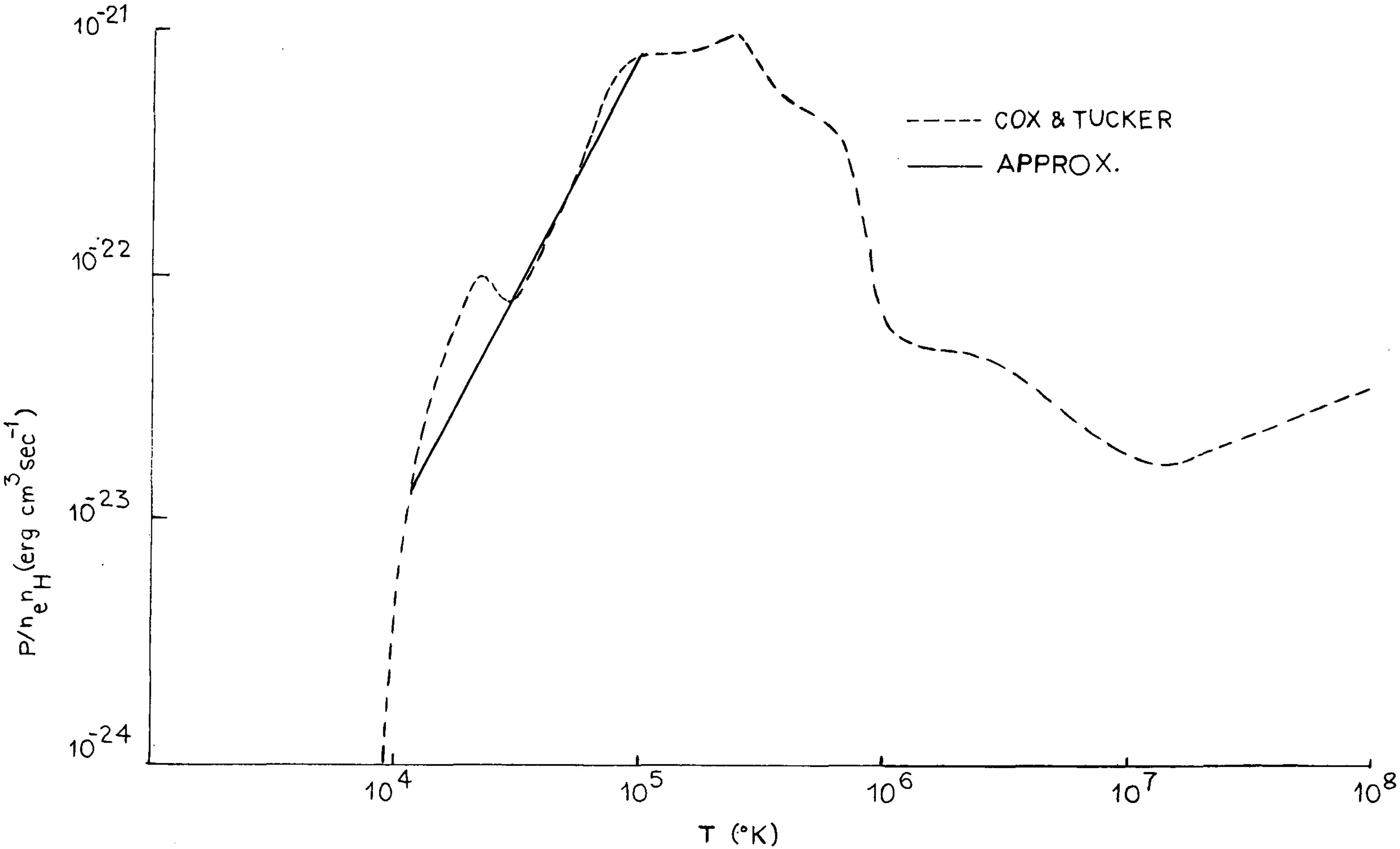

Figure 1. Total radiative power loss assuming cosmic abundances. Dotted line is by Cox and Tucker (1969); solid, the approximation $\Lambda(T) \propto T^{1.857}$.

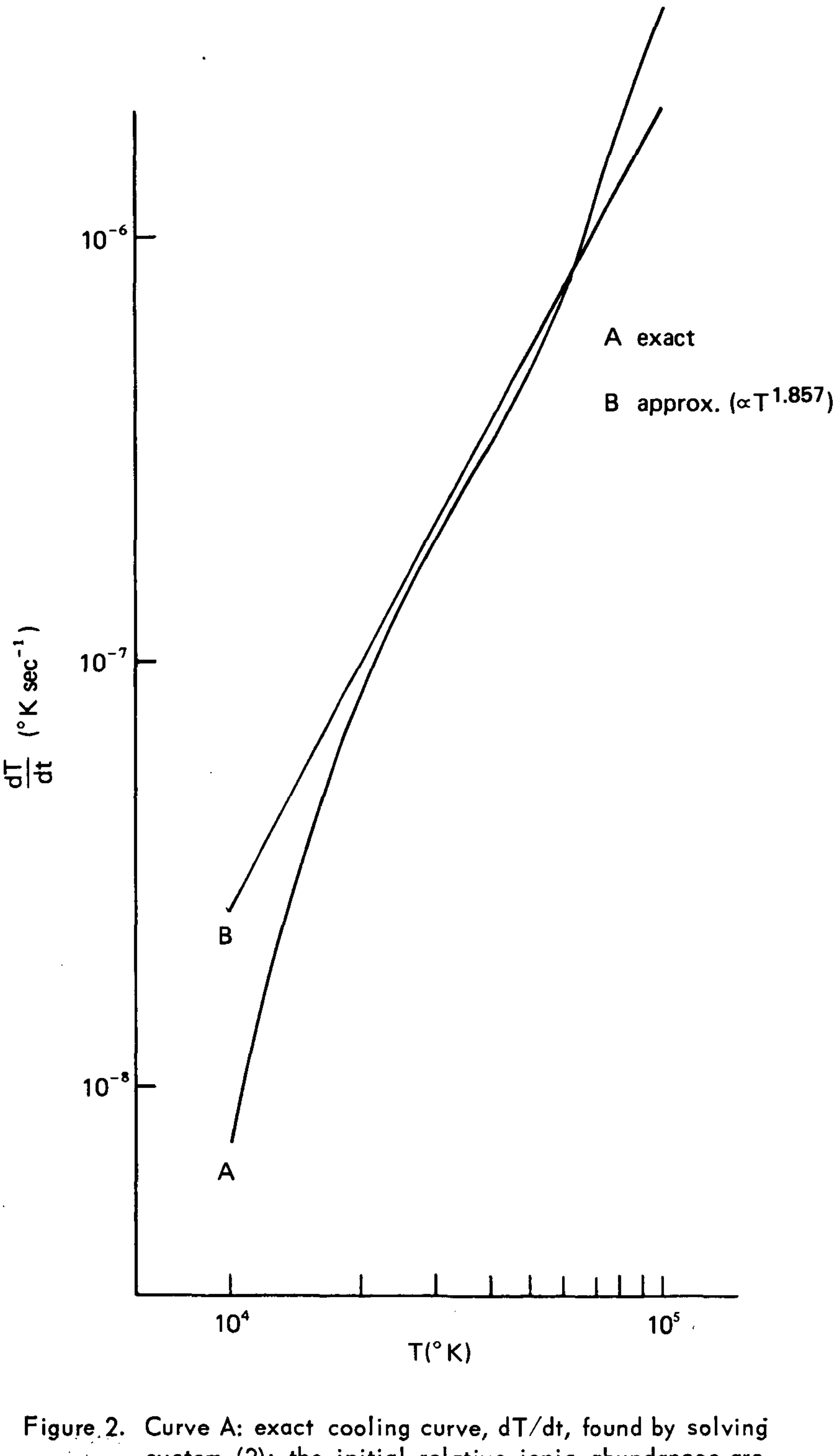

Figure 2. Curve A: exact cooling curve, dT/dt, found by solving system (2); the initial relative ionic abundances are $H^{+} = 1$, $He^{+} = 1$, $C^{++} = 1$, $O^{++} = 1$. Curve B: the approximation $\frac{dT}{dt} \propto T^{1.857}$.

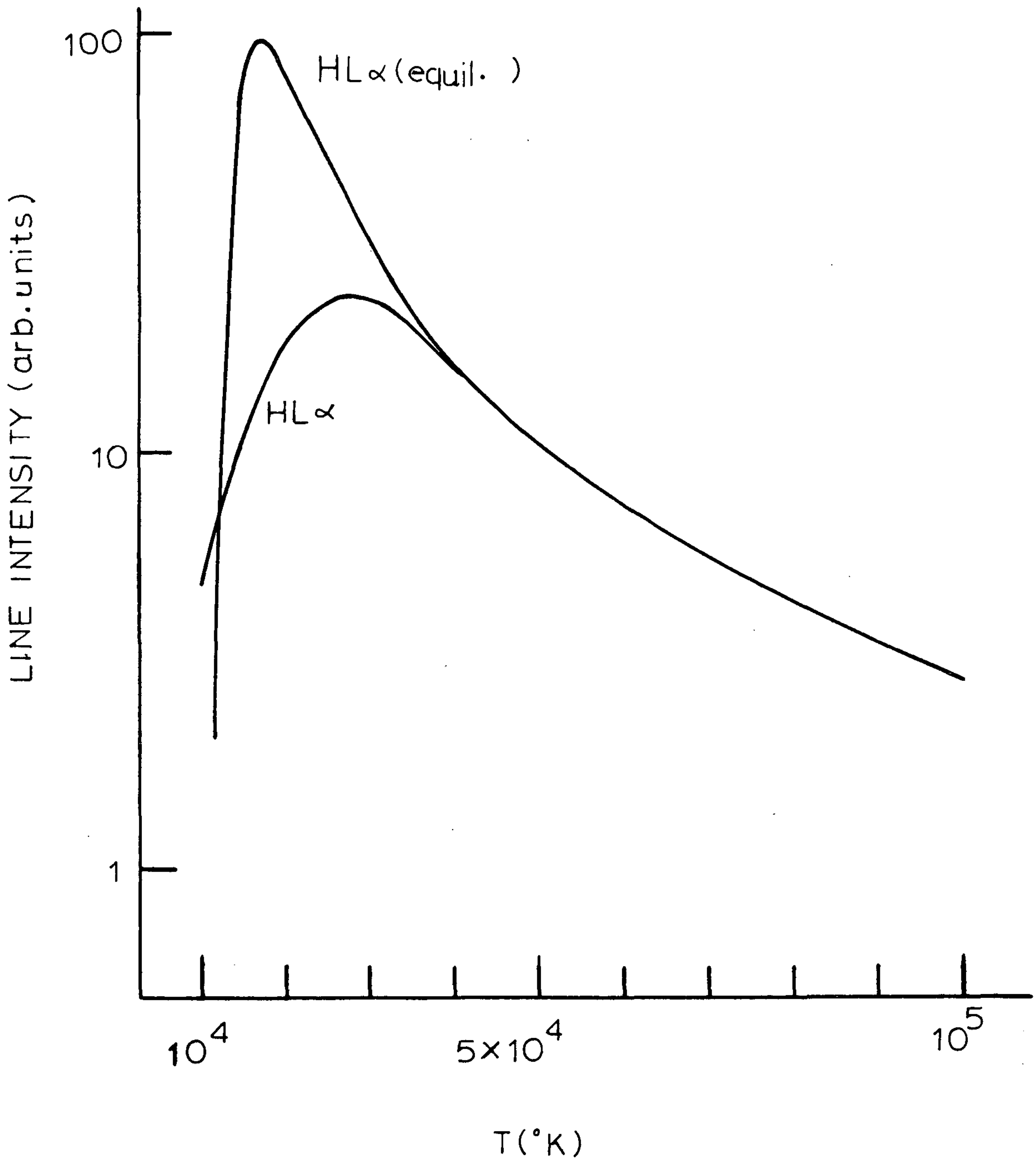

Figure 3. Intensity of the hydrogen Lyman-alpha line if recombinations balance ionizations (HLα (equil.)), and in the time dependent case (HLα) for the initial conditions of Figure 2.

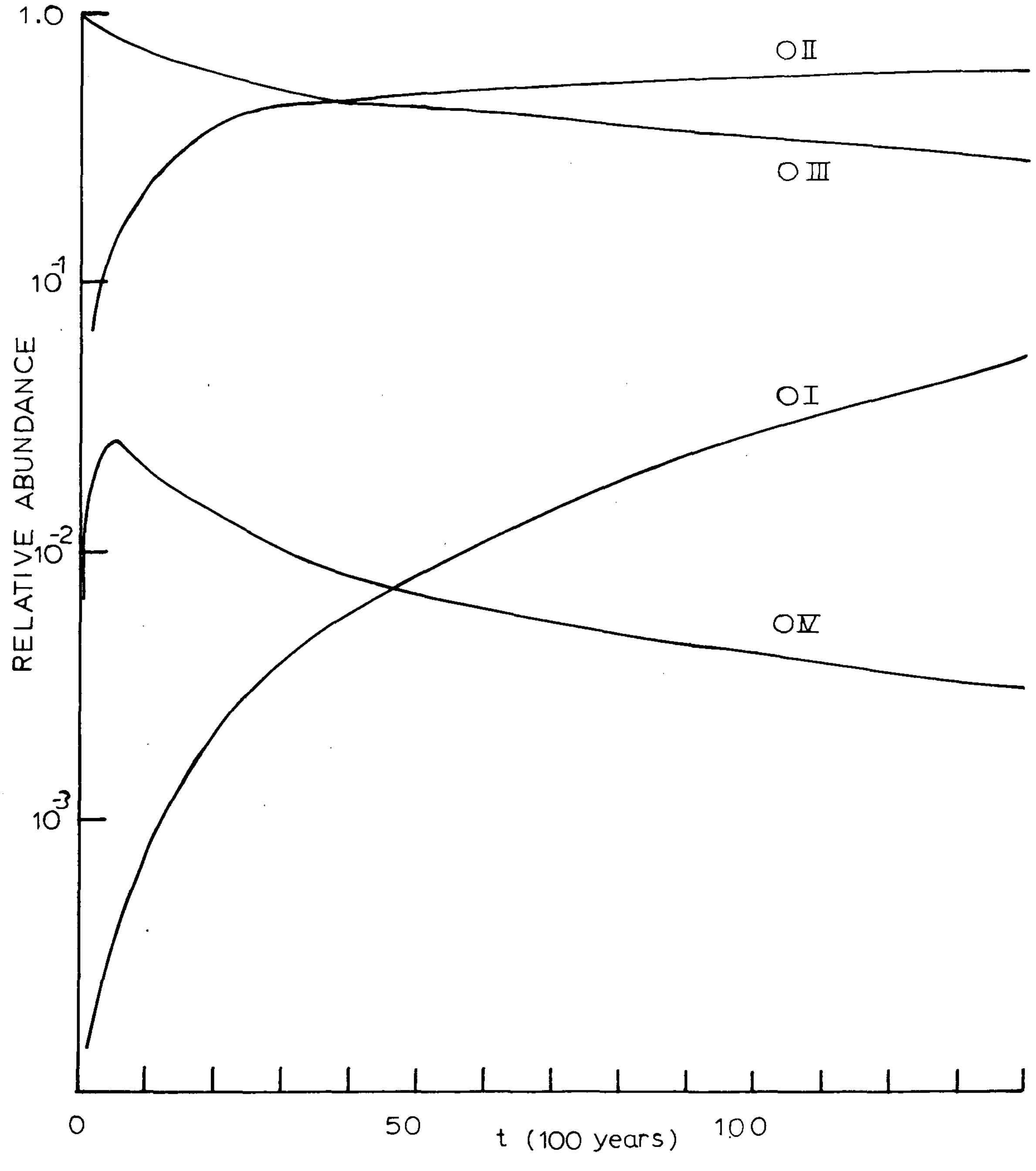

Figure 4. Relative abundances of oxygen ions as a function of time (initial conditions same as before). The unit of time is 100 years.

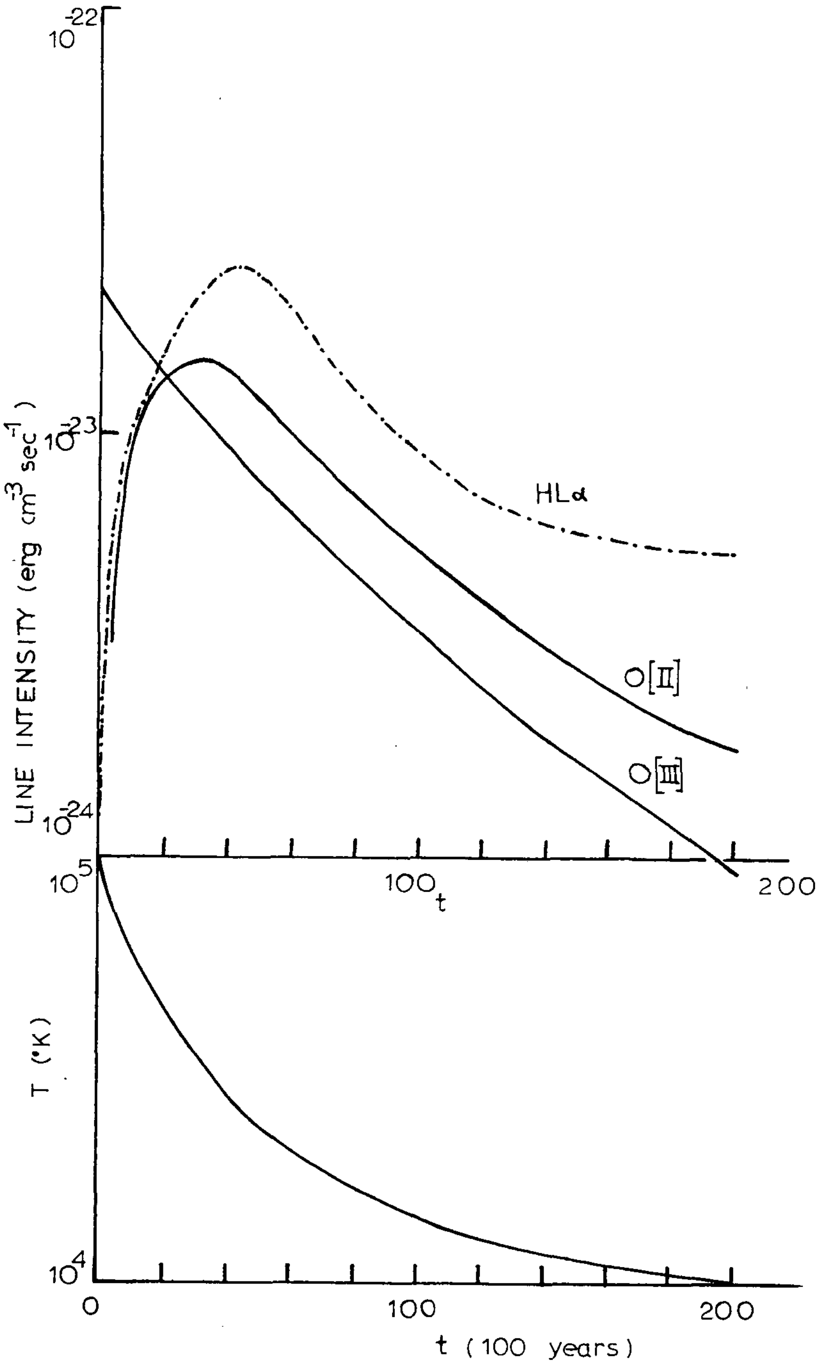

Figure 5. Volume emission rate (erg cm^{-3} sec^{-1}) of the hydrogen Lyman-alpha and the O [II], O [III] lines as a function of time. The temperature of the region is also shown (initial conditions same as before).

DISCUSSION

A. B. Underhill: Shouldn't you see the forbidden N II lines in the H-alpha region, for Tycho?

M.C. Kafatos: We have not calculated their brightness.