DYNAMICAL STUDY OF AN H II REGION*

SABATINO SOFIA†

Institute for Space Studies
Goddard Space Flight Center, New York
and
Department of Astronomy
University of South Florida

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A study of the "equilibrium region" left behind the expanding ionization front in an H II region is performed in order to investigate the influence of the usually neglected dynamical effects in the structure of the region.

To that effect, we consider a 40,000° K star surrounded by an H II region with an initial electron temperature of 10,000° K, and an initial electron density of 100. The gas is allowed to heat up, cool down, and move according to general hydrodynamic equations. It is found that after about 15,000 years the gas has relaxed to the same temperature found by the static treatment, and that while small velocities (due to the gravitational attraction of the star) and density differences have developed, they are not significant. In consequence, a static treatment for the "equilibrium region" is perfectly adequate, unless one is looking for transient effects of a time scale below about 15,000 years.

I. Introduction

The structure of that portion of an H II region left behind by the outwardly propagating ionization front, usually referred to as the "equilibrium region," has in recent times been the object of a large number of studies. The fundamental assumption underlying most of the work is that dynamical effects can be entirely neglected in determining the local properties of the gas, in particular its temperature distribution (c.f., Hjellming 1966; Sofia 1967, hereafter referred to as Paper I; Rubin 1968). It was pointed out in Paper I, however, that this assumption leads to an inconsistency in the models, since a homogeneous nebula in thermal equilibrium produces temperatures which vary with the distance from the central star. The resulting pressure differences drive mass motions which must destroy both the homogeneity and the static state of the region. As soon as the local density changes, however,

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†NAS-NRC Postdoctoral Research Associate.

the heating and cooling also change, modifying the original thermal balance and causing new mass motions.

Since this is a feedback process, for which the quantitative behavior cannot be reliably estimated a priori, it is useful at this time to consider the problem in the framework of a general dynamical treatment.

Section II describes the dynamical and thermal equations, and Section III contains the results and discussion.

II. Dynamical and Thermal Equations

As usual, the dynamical behavior of a fully ionized nebular region in the absence of a magnetic field is described by the following basic equations.

Continuity
$$\frac{d\rho}{dt} + \rho\, \nabla \cdot \mathbf{v} = 0 \tag{1}$$

Equation of motion
$$\rho \frac{d\mathbf{v}}{dt} + \nabla p + \rho \frac{G M_*}{r^3} \mathbf{r} = 0 \tag{2}$$

Energy balance
$$\frac{dp}{dt} = \frac{5}{3} \frac{p}{\rho} \frac{d\rho}{dt} + \frac{2}{3}[H - L] \tag{3}$$

where
$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \quad ,$$

ρ is the density, v is the velocity, p is the pressure, G is the constant of gravity, M_* is the stellar mass, r is the distance from the center of the star, H is the kinetic energy gain of the electron gas per cm^3 per sec, and L is the kinetic energy loss of the electron gas per cm^3 per sec.

In equation (3) the conductive term has been omitted, since its influence is negligible outside shock fronts and these do not exist in the equilibrium region.

The usual procedure in determining the nebular temperature has been to take a homogeneous nebula with a given density, and to find the temperatures for which $H = L$. All the other terms of the system of equations (1) through (3) were constrained to be zero. These restrictions are here eliminated. In solving the system of equations, we assume spherical symmetry and use the Eulerian approach (c.f., Sofia and Hunter 1968). The thermal treatment of the problem, which is wholly contained in the H and L terms of equation (3), has been discussed in previous publications, and in detail in Paper I. In brief, the energy gain of the electron gas is due to photoionization by the ultraviolet photons coming from the central star. In this paper the model of the central star was taken from Mihalas (1965).

The energy loss is evaluated including free-free transitions (which are almost negligible in all temperature ranges encountered here) plus the spontaneous emission from collisionally-populated low-lying energy levels of 50 ions of the ten most abundant elements. The ionic populations are computed at each mesh point each step in time using the Burbidge, Gould, and Pottasch (1963) approach, which takes into account the effect of the recombination radiation to the ground state (c.f., discussion in Paper I).

The numerical code used was shown in test runs and in previous work to be very accurate even in conditions less well behaved than the ones considered in this investigation.

III. Results and Discussion

The initial nebular model is a homogeneous, optically thin, spherical shell of radius 2.5×10^{18} cm, $N_e = 100$ and $T_e = 10{,}000°$ K. (The boundary of this region is approximately the boundary of the Strömgren sphere for the H II region).

The initial velocity of the nebular gas is assumed to be zero throughout. Very soon along the calculations, however, before anything has happened to the other quantities, small negative velocities develop in the nebula. The radial dependence of v indicates that it is due to the gravitational attraction by the central star. In practice, this gravitational attraction is probably offset by radiation pressure, which is not included in this study. Therefore, no special physical meaning is attached to these velocities (which always remain very small).

In a similar fashion, very little happens to the density distribution, which, except near the boundaries constantly remains close to the original value of $N_e = 100$.

A more interesting quantity to follow is the temperature behavior, which is displayed in Figure 1, where we can see the original

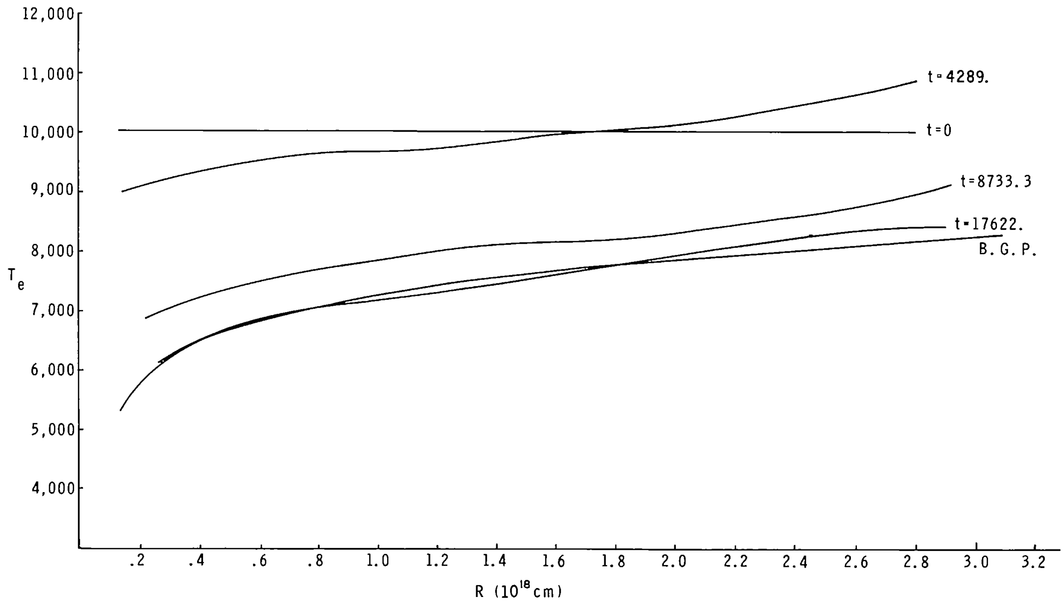

FIG. 1 — Electron temperature of the H II region as a function of distance from the central star for different times (in years). The curve labeled B. G. P. was obtained by the static treatment.

temperature distribution, and the temperature structure of the nebula after 4300 years, 8700 years, and 17,600 years respectively. After 8700 years the temperature distribution is close to the distribution obtained in the static approach, which is also displayed in the figure. The agreement becomes nearly perfect after about 17,000 years and remains that way thereafter.

Consequently, unless one is interested in considering transient phenomena of a short lifetime (say below 15,000 years), the static approach to the problem is completely adequate, and one can avoid the lengthy calculations involved in a dynamical treatment of the problem without any loss of information.

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REFERENCES

Burbidge, G. R., Gould, R. J., and Pottasch, S. R. 1963, *Ap. J.* **138**, 945.
Hjellming, R. M. 1966, *Ap. J.* **143**, 420.

Mihalas, D. 1965, *Ap. J. Suppl.* **9**, 321.
Rubin, R. H. 1968, *Ap. J.* **153**, 761.
Sofia, S. 1967, *Ann. d'Ap.* **30**, 377.
Sofia, S., and Hunter, J. H., Jr. 1968, *Ap. J.* **152**, 405.