H II REGIONS: SOME THEORETICAL DEVELOPMENTS

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Abstract. Observations have revealed the presence of inhomogeneities in both density and velocity in H II regions. Dense non-ionized condensations can persist for a long time, developing bright rims of dense ionized gas around them. Attempts have been made to understand the large ~50 km s^{-1} motions seen in some H II regions by invoking stellar winds or the flow of cosmic ray particles through the plasma.

I. Introduction

It has long been known that the structure of H II regions is not homogeneous. In particular, the electron density n_e is often uneven, and there are frequently considerable differences in velocity between adjacent parts of an H II region.

The unevenness in electron density shows up when attempts are made to determine $\bar{n}_e$ by means of different techniques. To understand how this happens, suppose that a fraction α of the available space contains electrons, at a density of N_e per unit volume, and that the rest of the space is empty. Then a measurement of the electron density by the technique of line ratios will find the average value

$$\bar{n}_{e,1} \equiv \frac{\int n_e \, dn_e}{\int dn_e} = N_e, \tag{1}$$

since the mean is, in this case, weighted by the local ion, and therefore electron, density. A determination based on the emission measure of the H II region will find the value

$$\bar{n}_{e,2} \equiv \left\{\frac{\int n_e^2 \, dl}{\int dl}\right\}^{1/2} = \left\{\frac{\int n_e^2 \, dv}{\int dv}\right\}^{1/2} = \alpha^{1/2} N_e. \tag{2}$$

Finally, a determination based on pulsar dispersion measure would, if it could be carried out unambiguously, find the value

$$\bar{n}_{e,3} \equiv \frac{\int n_e \, dl}{\int dl} = \frac{\int n_e \, dv}{\int dv} = \alpha N_e. \tag{3}$$

Discrepancies between known results show that the filling factor is around 0.03 to 0.05 (Osterbrock and Flather, 1959; Danks and Meaburn, 1971).

The velocity structure of H II regions is also noticeably uneven. Thus the observations of the Orion nebula by Wilson *et al.* (1959) revealed velocity differences between adjacent regions of the order of 10–20 km s^{-1}. More recently Meaburn and his associates have found rather larger velocity differences in various nebulae, ranging up to 50 km s^{-1} (see, for example, Meaburn, 1971). In this case the linear scale on which the variation occurs may be rather larger.

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II. The Effect of Non-Ionized Condensations

The temperature does not vary much from point to point in an H II region, so that any fluctuations in electron density must be strongly correlated with pressure fluctuations. It is therefore natural that irregular gas flows should occur in H II regions, typically with velocities of the order of the speed of sound. This is just what Wilson and Münch observed.

But the inhomogeneities in density and pressure occur on a small linear scale, perhaps 10^{16} or 10^{17} cm. If the resulting motions have speed of about 10^6 cm s^{-1} then the density of the ionized gas will even itself out in a short time, of the order of 1000 yr. This is clearly much less than the age of the typical H II region. The suggestion has therefore been made that the spaces where there is high electron density are associated with condensations of non-ionized gas, embedded in the H II region. Around the boundary of each condensation there is an ionization front, itself surrounded by a shell containing dense ionized gas (a bright rim). The gas in the bright rim streams away from the condensation into the lower density H II region.

Quite a long time ago Dyson (1968) worked out these ideas in some detail and found reasonable agreement with the observed phenomena. His model for a non-ionized globule with its ionized jacket was later reconsidered (Kahn, 1969); the main change in this revised version was that it gave a different treatment of the mechanics of the ionization front. Qualitatively the results were not changed much. Both treatments were restricted to condensations which had spherical symmetry throughout. Naturally the incident radiation field must then be isotropic. Such an idealisation makes the theory easier to handle, but obviously it cannot give a realistic description of the radiation field in an actual H II region.

It is therefore interesting that Dyson (1973b, 1974) has made a first attempt to extend his description to cases where the incident radiation field is anisotropic. His treatment is linearized, in the sense that it allows for small distortions from spherical symmetry. Once again the problem is to calculate the structure of the non-ionized part of the globule, and to fit the solution to the appropriate boundary conditions at the ionization front. Dyson concludes that the distortions in the globule are usually rather smaller than the anisotropy of the radiation field.

However, the discussion is rather a delicate one. The boundary conditions applicable to the anisotropic case have to be found by making an analogy with the isotropic situation. It is arguable whether Dyson has used the proper analogy, but there will probably be no qualitative change in his overall conclusion even if he has to revise his boundary conditions. So we conclude, provisionally, that the existence of a globule does not depend on its being spherically symmetrical; globules can therefore exist in much the same way in real radiation fields.

If a globule does not collapse under its own self-gravitation, it will provide a source of high density ionized gas until it has been eaten up by the incident Lyman continuum radiation. The complete ionization of a globule would typically require a few hundred thousand years.

III. Other Causes of Inhomogeneity

The presence of non-ionized condensations within H II regions probably explains the existence of density fluctuations in the ionized gas, and produces the irregular velocity pattern described by Wilson and Münch. But it is rather less likely that the 50 km s^{-1} motions observed by Meaburn can be explained in the same way.

To understand why there may be a difficulty, let us consider the steady flow of ionized gas from a globule. It is most realistic to assume that the gas remains isothermal, at a temperature of about 10^4 K. With the usual cosmic mixture of elements, the corresponding speed of sound is $c_0 = (kT/m)^{1/2} = 1.2 \times 10^6$ cm s^{-1}. For a steady flow, Bernoulli's theorem takes the form

$$\tfrac{1}{2}u^2 + c_0^2 \log \varrho = \text{constant}, \tag{4}$$

where u is the speed and ϱ the density of the gas. If the density is ϱ_I and the speed $u_I \equiv \mu_I c_0$ at the ionization front, then it follows from (4) that elsewhere in the flow

$$\frac{\varrho}{\varrho_I} = \exp\left\{-\frac{u^2 - \mu_I^2 c_0^2}{2c_0^2}\right\}. \tag{5}$$

With $\mu_I = 2$, $u = 5 \times 10^6$ cm s^{-1} and $c_0 = 1.2 \times 10^6$ cm s^{-1},

$$\frac{\varrho}{\varrho_I} \doteqdot e^{-7} \doteqdot 10^{-3},$$

so that the gas flow reaches a high velocity only after the density has fallen by a large factor. At very low density the gas contributes only a little to the emission measure. It would therefore be quite hard to explain Meaburn's observations in this way. On the other hand, compared with the luminous output of an O5 star, it does not require an extravagant amount of energy to set up the 50 km s^{-1} motions. Much of the energy radiated by the early type stars in H II regions is, in fact, given to the gas, but the gas re-radiates it in turn, and only a little remains available to drive any mass motions. A good mechanism for the acceleration of the gas requires that energy be stored, for a long enough time, in a form where the particles or photons carrying it have a momentum density which can couple with the gas in the H II region. The problem is not that the energy requirement is excessive, but rather that it is not easy to retain the energy in a suitable form.

Dyson and de Vries (1972) (see also Dyson, 1973a) have investigated whether a powerful stellar wind can drive high speed motions through an H II region. A speed of 1500 km s^{-1} is adopted for the wind; it turns out that the wind will form an expanding hole in the interstellar gas. Beyond the boundary of the hole there is a highly compressed layer of gas, which is itself enclosed on the outside by a shock, S_1. Inside the hole there is a thick shell of hot gas, bounded on the interior side by an inward facing shock, S_2. As the wind from the star passes through this shock, its kinetic energy is converted into thermal energy. For a wind speed of 1500 km s^{-1}, the shocked gas acquires a temperature of the order of 10^8 K. Little cooling is expected to occur in so hot a gas. Instead the shock-heated gas pushes against the surrounding interstellar gas. In short, the stellar wind can be regarded as a source of thermal energy which pumps pressure into the hole in the interstellar gas and causes it to expand.

The result of the calculation is that about 25% of the energy released in the stellar wind becomes available in the form of mass motion in the interstellar gas. The rest is lost as thermal energy behind shock S_1, and is later radiated. As an example, if the stellar wind relases energy at a rate $Q = 10^{38}$ erg s^{-1}, and blows into interstellar gas having a density $\varrho_0 = 10^{-22}$ g cm^{-3}, then the interstellar gas will move at a speed $V = 5 \times 10^6$ cm s^{-1} after time $t = 10^5$ yr. For different values of Q, ϱ_0 and t, V scales like $(Q/\varrho_0 t^2)^{1/5}$. Dyson considers a rather smaller value for Q, and is somewhat pessimistic about the likely significance of stellar winds in this context; nevertheless, it seems that this process may actually be quite important. In particular it is worth noting that Wendker, Smith, Habing, Israel, Dickel and Price consider that a stellar wind, originating in the WR star HD 192163, may be responsible for forming the ellipsoidal nebulosity NGC 6888 (Lindsey Smith, private communication). The nebulosity would here be identified with the compressed interstellar gas lying between the contact discontinuity and shock S_1. The ellipsoidal shape of the nebulosity is interesting, and doubtless arises from an anisotropy in the stellar wind itself. It will be interesting to modify Dyson's calculations to allow for departures from spherical symmetry, and to see what restrictions this change places on the model.

There are other possible ways of storing the energy, for example in the form of cosmic ray particles. As is well known, cosmic rays readily lose energy to free electrons via electrostatic interactions. If cosmic ray protons are trapped in an ionized gas with density 10^{-22} g cm^{-3} then the time scale for this energy loss exceeds 10^5 yr, provided the protons have a kinetic energy greater than 160 MeV. For other densities the minimum energy scales like $\varrho^{2/3}$. Clearly suprathermal particles, whose energies are supposedly around 5 MeV, will not last long enough to provide any important acceleration, unless they can be prevented from mixing with the interstellar gas. But cosmic rays in the more usual energy range will last long enough. The mechanical coupling between the cosmic ray plasma and the thermal plasma is due to the well-known Alfvén wave instability. This effect prevents any streaming between the two plasmas with relative speeds substantially greater than the Alfvén speed (Kulsrud and Pearce, 1969; Skilling, 1970; Kahn, 1971). It is now thought that this effect is not quite as universally important as had once been believed, largely because damping of the Alfvén waves by ion-neutral collisions restricts the range of conditions where the wave instability occurs (Wentzel, 1974). But this certainly does not apply in H II regions.

Finally, to complete the list of energy sources, there may be mechanical effects caused by very low frequency radiation trapped in the H II region. The vlf radiation is thought to originate in pulsars, and on emission the period $2\pi/\omega$ of a wave is the same as the pulsar period. The wave cannot propagate through a plasma of electron density n_e unless the amplitude A of its vector potential exceeds $A_* = 4\pi n_e e c^2/\omega^2$. Even when a wave does propagate, it is still unstable on a short time-scale and is therefore expected to break up into secondary waves having a different frequency (Max, 1973). Non-linear interactions occur once the plasma contains waves with a variety of frequencies. The interactions impede propagation, so that once again energy is trapped in the H II region, and becomes available for accelerating the interstellar gas. But here we are on very speculative ground, for these ideas have not really been worked out yet.

All these processes should have about the same efficiency for the conversion of energy into kinetic energy of the ionized gas. In other words, to explain the 50 km s^{-1} motions we must look for a source which will provide energy at the rate of about 10^{38} erg s^{-1}, in a form which does not rapidly get lost as radiation, and will maintain the supply for some 10^5 yr.

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DISCUSSION

J. R. Dickel: The high velocity wings all appear on one side. Is it positive or negative radial velocity? And won't the spherical expanding shocks or stellar winds produce a symmetric profile with wings on both sides?

Kahn: The early observations by Meaburn showed high velocity streaming on the negative side only. I believe that it is not yet quite certain whether this asymmetry is real. If it is, then a spherically symmetrical stellar wind will not offer any explanation of this phenomenon.

Yuan: Those profiles which you showed all have a narrow central peak and broad tails. But your stellar wind model seems only capable of producing a simple Gaussian. How do you explain?

Kahn: The H II region at large produces a narrow spectral line. The broad wings would be due to the emission from the region where the gas is expanding at ~50 km s^{-1}.

Habing: What is the evolution of the kind of globules you showed? Provided that they do not collapse, will they gradually dissolve, forming thin shell sources of ionized gas, or will they form dense ionized blobs?

Kahn: The massive blobs collapse under gravitation. In the less massive ones the gas becomes ionized and streams away into the surrounding H II region.

Parijskij: We may simplify the picture of the OH (and H_2O) emission by a suggestion that many observable features are due to propagation effects, through a moving ionized (and neutral) medium.

Example: a strong stellar wind is between the primary single source at a single frequency and the observer. We should expect in this case a multi image structure and a separation of R and L-handed polarized spots. The physical conditions in that case do not seem extreme.

Swarup: Would you be able to identify these compact sources in the microwave region?

Kahn: No, I don't think so. No star has get condensed inside these globules. When they are illuminated from inside they look quite different, they become infrared sources, perhaps eventually compact H II regions.

Dickel: For a 10 $M_\odot$ globule what is the size?

Kahn: The size is 10^{16} cm.

Pishmish: In the region of NGC 2467 over a very small region of 0.5 pc there is a radial velocity difference of 50 km s^{-1} (that makes it 50 again).

Terzian: Do we expect to see these sources in radio recombination lines?

Kahn: I don't see why not.

Menon: Some years ago photographs were taken of the Orion nebula by Fisher at the University of Hawaii with very narrow band filters which could be tuned around Hα. Photographs were taken every 2–3 km s^{-1} over a wide range of velocities, and again they showed a component at about -50 km s^{-1}.