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DYNAMICS OF IONIZED REGIONS

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1. Introduction. — Early type stars emit a large proportion of their radiation at wavelengths beyond the Lyman limit of hydrogen. This radiation can photoionize atomic hydrogen and other elements in surrounding interstellar gas. The photoionization of hydrogen and, to a lesser extent, of helium, is a source of energy input for the gas. The kinetic energy of the photoelectrons is rapidly shared out amongst other particles by collisions. The particle velocity distributions are Maxwellian defined by the electron temperature \( T_e \). If the gas were composed of hydrogen and helium only, \( T_e \) would be about \( 2 \times 10^4 \) K. However, the temperature of actual ionized interstellar gas is significantly lower because of the cooling effects of impurity elements such as oxygen and nitrogen. These elements exist as singly or doubly ionized ions which have low lying metastable energy levels within their ground state configurations. These levels can be excited by inelastic electron collision. They decay by the emission of photons which escape freely from the gas. The reduction in the thermal energy content of the electrons is equivalent to cooling the gas as a whole. This cooling is very efficient and acts as a fairly precise thermostat for the gas. The electron temperature is typically about \( 8 \times 10^3 \) K, and the gas can be regarded as isothermal to a very good approximation even if shock waves appear in the flow. The cooling is so efficient that shocked gas cools off in a very thin layer behind the shock wave. A shock wave within the ionized gas therefore produces a compression about equal to the square of its upstream mach number.

In the simplest model of an ionized region, the star is surrounded by a region of essentially fully ionized hydrogen whose volume is determined by the balance between the rate of recombination and the rate of output of stellar U. V. The transition zone between the ionized and neutral material (the ionization front) has a thickness of approximately the mean free path of a Lyman continuum photon in the neutral material, and can almost always be regarded as a discontinuity. The pressure in the neutral gas is about two orders of magnitude less than that of the ionized region which therefore expands with a velocity of about \( 10 \) km.s\(^{-1}\). Actual diffuse nebulae are far from homogeneous and contain internal pressure gradients which cause local motions of ionized material. Again these motions have velocities of the order of the sound speed in the ionized gas (\( \approx 10 \) km.s\(^{-1}\)).

2. Interaction of stellar winds with the ionized gas. — There is considerable observational evidence that the OB supergiants which excite HII regions have mechanical as well as radiative energy outputs. This mechanical energy output manifests itself in the form of a high velocity stellar wind. The terminal velocity in the wind is typically \( \approx 2 \times 10^5 \) km.s\(^{-1}\). The mass loss rates are more uncertain with perhaps \( 10^{-6} \) M\(_\odot\) year\(^{-1}\) being the canonical value. Thus the mechanical energy output in the wind is \( \approx 10^{36} \) erg.s\(^{-1}\). This is \( \approx 1 \% \) of the energy output from the star in the Lyman continuum. However, the efficiency of its dynamical interaction with surrounding matter is much higher than the efficiency of conversion of radiant energy into mechanical energy in the surroundings and its effects are of considerable importance.

The idealized flow pattern resulting from the impact of the wind with uniform surrounding gas is shown in figure 1. Two shocks occur; an inwards facing shock, \( S_2 \), in the stellar wind, and an outwards facing shock \( S_1 \) in the ambient gas. The shocked stellar wind gas is raised to a very high temperature (\( \sim 10^7 \) K) and can cool only slowly. It is generally a good approximation to treat this gas as adiabatic. At all except the earliest times, the shocked ambient
gas cools back to a temperature about equal to its original (unshocked) temperature which is maintained by the stellar U. V. flux. Shock $S_1$ is therefore an isothermal shock and the compression of ambient gas is determined by the mach number of $S_1$ (if the interstellar magnetic field is ignored). The compression ratio across $S_1$ may be extremely high ($\approx 100$) and hence the shell of swept up material is extremely thin. The recombination rate within this shell increases with time and eventually the ionization front (which initially lies ahead of $S_1$) may become trapped within the shell. Unless the ambient density is extremely high, this happens when the velocity of $S_1$ is comparable with the sound speed in the ionized gas. This effect may not happen if there are other OB stars nearby to increase significantly the U. V. radiation field incident on the shell. Further, the inclusion of an interstellar magnetic field does not significantly alter the dynamics of the shell but may reduce its interior density. The recombination rate within the shell would be reduced and trapping of the ionization front becomes less likely. It is probably a good approximation to regard the moving shell as ionized until it stalls. The efficiency of conversion of stellar mechanical energy output into kinetic energy of swept up material is about 20%.

3. Application to observed motions in nebulae. — The observed velocity structure of diffuse nebulae is extremely complex. Several nebulae exhibit broad and sometimes clearly split optical emission lines. The indicated velocity dispersion in the ionized radiating gas is $\approx 40$ km s$^{-1}$ which implies supersonic motions. Contributions to these motions may arise from several effects, for example, the expansion of ionized gas from the surfaces of neutral intrusions within the ionized region. Undoubtedly the interaction of stellar winds with the gas as described above also plays a role. A further interesting feature of these observations is the presence in some nebulae of faint emission line peaks shifted by about 70 km s$^{-1}$ with respect to the main emission peaks. It is impossible to produce these features by simple expansion processes involving pressure gradients in the ionized gas. The increase of velocity by expansion is bought at the expense of gas density and the emission falls off too rapidly to give observable features. It is possible to produce these velocities over reasonable timescales ($\approx 5 \times 10^4$ years, say) by stellar winds provided the energy output in the wind is high enough ($\approx 10^{37}$ erg s$^{-1}$). There is observational evidence that at least some OB stars have mechanical energy output rates of this order. However, simple spherically symmetric models do not predict one very important feature of the observations. The faint high velocity features are always blue shifted (i. e., approaching the observer) with respect to the main line peaks.

One possible resolution of this difficulty is to relax the simple model of a uniform nebula surrounding the exciting star. There is now considerable evidence that many diffuse nebulae are located at the front edges (with respect to the observer) of more extensive neutral clouds. This situation is depicted schematically in figure 2. Ionized gas is continuously fed into the nebula by the action of stellar U. V. on the extended cloud. This gas expands away from the ionization front into much lower density surroundings. The gas density decreases with increasing distance from the neutral cloud. A stellar wind from a star within this ionized region will move into gas containing pronounced density gradients. The portion of the shell of swept up material moving away from the observer (which would produce an emission feature redshifted relative to the main line peak) moves into regions of increasing density. It therefore decelerates rapidly. Conversely the portion of the shell moving towards the observer moves into regions of decreasing density and hence decelerates much more slowly. The blue shifted emission features would then be identified with emission
from this part of the shell. Simple computations show that this scenario is plausible.

4. Other possible effects of stellar winds on nebulae. — The dynamical effects of stellar winds on nebulae may produce morphological features which can be directly observed. A possible example lies in the galactic nebula S 206. Figure 3 is a sketch of this region, following a photograph taken by Dr. L. Dehaveng in the 5 007 Å of doubly ionized oxygen. Of particular note is the half ring of nebulosity centred on the exciting star. The presence of bright rim structures shows also that the nebula itself is formed at the edge of a neutral cloud. A possible explanation of this half ring is that ionized gas streaming from the ionization front on the neutral cloud interacts with a stellar wind from the exciting star. The half ring is interpreted as ambient material behind a stand-off shock produced by the interaction of streaming nebular gas and stellar wind material. A simple steady state model indicates that the star must have a mechanical energy output rate of about $10^{36}$ erg s$^{-1}$. This is entirely consistent with observational estimates for other O stars.

The hot shocked stellar wind region shown in figure 1 may also play a role in the confinement of density fluctuations within nebulae. It has long been known that in many nebulae, the ionized gas occupies only a small fraction of the available volume. For example, in the Orion Nebula, most of the optical emission from the central regions comes from about 2 % of the volume. It is extremely difficult to see how such a high degree of concentration can exist for more than a few hundred years unless these small regions are regenerated or maintained. One possibility is certainly that small condensations of ambient gas are trapped within the hot shocked stellar wind gas and maintained in pressure equilibrium. There is some evidence that these condensations must have neutral cores. It is difficult to account for the relative abundances of singly and doubly ionized ions of the same element (e.g. oxygen) without them. One possibility is that these globules are the remnants of subcondensations which were present in the original cloud in which the early type stars formed. Alternatively, there is the possibility that the compressive action of the stellar wind on condensations of ionized gas can increase their densities to such an extent that their cores become neutral. The dynamical interaction of the stellar wind with a discrete condensation of ionized gas is extremely difficult to calculate properly. However, order-of-magnitude calculations suggest that ionized blobs with neutral cores could be produced by the suggested interaction. The cores can remain neutral for timescales typically $\sim 10^4$ years, and therefore could be a sign of fairly recent stellar wind activity.

5. Conclusions. — Theoretically, stellar winds from OB stars are extremely important in the dynamics of ionized regions. They may contribute to the general levels of motion within the gas and may also be responsible for the high velocity features. Further they may produce important modifications to the structure of the nebula. The strongest support for these ideas would be actual observation of stellar winds from the O stars associated with given nebulae. At present, these observations are lacking.