ENERGY BALANCE IN THE INTERSTELLAR MEDIUM

E. E. Salpeter
Astronomy and Physics Depts., Cornell University

Abstract: A large number (approximately 7) of different components or phases are needed to describe the interstellar medium. The neutral intercloud medium is probably a composite of (a) "lukewarm, substandard" clouds (heated by grain photoeffect and shockwaves), (b) the interfaces between clouds and coronal gas and (c) some "phase 2" gas heated by soft X-rays. Ionizing UV photons are mainly produced by OB-stars and are responsible for most of the average electron density. Bulk kinetic energy for "stirring" the medium and soft X-rays are mainly produced by supernova remnants, less by O-star stellar winds.

1. INTRODUCTION

The energy balance in a molecular cloud is a special case and I will leave this topic for Turner's review. Before discussing energy balance I list (in Sect. 2) modern views on the various components, or "phases", of the interstellar medium. Sect. 3 deals with mass balance, or turnover rates, and Sect. 4 with energy balance itself.

Although the energy input takes on different forms, the primary energy source mainly resides in individual stars. Spiral density waves, powered by rotational and gravitational energy of the galactic disk, are an exception. These density waves--in producing shocks which may initiate star formation (see, in particular, Wielen's and Woodward's contributions)--are triggering mechanisms more than primary energy sources. There is controversy between different rival stellar sources, such as supernova remnant versus O-star stellar wind and nuclei of planetary nebulae versus B-stars. Part of the controversy concerns the precise threshold mass for various processes, so I want to review just what is sensitive to mass and what is not:

For the stellar population I, which applies to the overall Galactic Disk, there is a turnover in the mass-function near 0.2 $M_\odot$ and a main sequence break-off near 1 $M_\odot$. As regards the present-day luminosity function ψ, massive stars are rare and get rarer rapidly

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with increasing mass. However, for energy balance considerations it is not ψ itself that matters but mass and energy "fluxing rates", which are related more directly to the birthrate function or "initial mass function" (IMF). A key feature of star formation in the galactic disk is the fact that stellar mass M times (IMF) is a very slowly varying function of M, roughly $\propto M^{-1/3}$ for $M>0.2\ M_\odot$. As a consequence, the fraction of total mass used in star formation which goes into stars of mass $M>1\ M_\odot$ has a total nuclear energy output proportional to M, the fraction of total integrated luminosity $\int Ldt$ which comes from stars with mass larger than M is also of order $(M/M_\odot)^{-1/3}$.

Initial main sequence masses larger than $\sim 10\ M_\odot$ are required for (a) the main sequence luminosity to be mainly in the Lyman continuum, (b) the eventual production of a supernova and (c) the generation of a high-velocity stellar wind. In fact, supernova statistics (Maza and v.d. Bergh 1976; Tammann 1977) suggest that the threshold for (b) may be $\sim 5\ M_\odot$ rather than $10\ M_\odot$; Copernicus data (Snow and Morton 1976; Lamers and Morton 1976) suggests that the threshold for (c) may be $\sim 20\ M_\odot$ rather than $10\ M_\odot$. However, because of the weak dependence of $(M/M_\odot)^{-1/3}$ this difference matters little. What matters more is the energy output per star: The main sequence integrated luminosity (msil) is $\sim 10^{-3}\ Mc^2$ and the supernova energy release ~ 0.05 (msil). The gravitational energy content of a main sequence star is only $\sim 10^{-3}$ (msil), O-star stellar winds usually flow at $\lesssim 3$ escape velocity, so that the bulk kinetic energy released in such a stellar wind is $\lesssim 9\times$(gravitational energy) $\sim$ 0.01 (msil). Hence O-star stellar winds are likely to be a smaller primary energy source than supernova remnants, but not by a large factor.

Another comparison concerns central stars of planetary nebulae versus OB-stars: Most stars above $1\ M_\odot$ can produce a planetary nebula (Weidemann 1977), whereas OB-stars are massive, but the important question is what fraction of the (msil) is emitted in the far UV during and after the planetary nebula stage. There was enough theoretical uncertainty (Salpeter 1978) so that fraction might have been appreciable. However, recent UV studies of surface temperatures (Pottasch et al 1978) indicate that this fraction is only ~ 0.01 and planetary nebulae are a minor UV source.

2. THE VARIOUS "PHASES" OF THE INTERSTELLAR MEDIUM

Spitzer (1956) pointed out that the different components of the interstellar medium (ISM) should be in rough pressure equilibrium with each other, much (but not all) of the time. The "two-phase model" (Field et al 1969, Dalgarno and McCray 1972) of the ISM was an elegant application of this principle. However, more recently a larger variety of ISM components (and "transient" material far from pressure equilibrium) have been discovered.

I reiterate first the most obvious components of "phases" of the

ISM in an "average" galactic disk. I assume a radius $\sim$13 kpc, half-height at half-density $\sim$130 pc, a hydrogen mass $M_H \sim 3\text{x}10^9\ M_\odot$ and average pressure (divided by k) of (1500 to 3000) cm^{-3} °K:

Phase 0: "Molecular cloud-OB-star complexes": Typical internal density $n \sim 10^3$ (H) cm^{-3}, temperature $T \sim 10$ K and an overall contribution to mean density of $\bar{n} \sim 0.4\ cm^{-3}$ (volume filling factor $f \sim 4\text{x}10^{-4}$). I will not discuss this phase further.

Phase 1: The "Standard" HI clouds: Internal density $n \sim 40\ cm^{-3}$, $T \sim 70$ K, $\bar{n} \sim 0.2$, $f \sim 0.005$. This component accounts for about half of the neutral atomic hydrogen.

The "Old" Phase 2: A hypothetical, ubiquitous intercloud medium, heated and partially ionized by a hypothetical, ubiquitous flux of X-rays or cosmic rays with ionizing rate per H-atom of $\zeta \sim 10^{-15} s^{-1}$: This, now partially abandoned, component would have had $n \sim \bar{n} \sim 0.2\ cm^{-3}$; $T \sim 7000$ K, $f \sim 1$ and an electron density $n_e \sim \bar{n}_e \sim 0.03\ cm^{-3}$. It would have accounted for the full $\bar{n}_e$ indicated by pulsar dispersion measures (Gómez and Guelin 1974) and the half of the neutral atomic hydrogen which is not strongly absorbing in the 21cm-line. The total flux of soft X-rays is not sufficiently large for a uniform phase 2, but there should be some of it with a slightly smaller internal n and a smaller filling factor (the temperature depends on ζ/n).

Phase 4-: The OVI-containing "coronal gas" (I label components in order of increasing temperature): This component is suggested by satellite observations of absorption by the OVI ion which occurs in gas in a narrow temperature range around $3\text{x}10^5$ K. An extrapolation from OVI column densities (Jenkins 1978) gives a contribution to the average density $\bar{n}$ from this component of $\sim 3\text{x}10^{-4} cm^{-3}$, but the filling factor is not known.

The evidence for further components is less direct and the following is my personal selection. I start with two components (1+ and 2-) which I feel are needed (together with 2) to account for the neutral atomic hydrogen which is "not strongly absorbing" (with $\bar{n} \sim 0.2\ cm^{-3}$):

Phase 1+: "Lukewarm" and "substandard" clouds: Evidence has been accumulating that the clouds display a wide range of temperatures. The latest absorption-emission survey (Dickey et al 1978a) confirms such "lukewarm" clouds with $T \sim (10^2$ to $10^3)$ K, contributing $\sim 0.1\ cm^{-3}$ to the average density. There is some anticorrelation between the temperature and the 21cm optical depth for these clouds. A measured temperature is only a harmonic mean along the line of sight, not necessarily a single physical temperature, but it is clear (Dickey et al 1978b, Baker 1978b) that mere blending of phase 1 and a uniform phase 2 is not sufficient.

Phase 2-: Interfaces: As mentioned, some phase 2 (neutral, but

$T > 10^3$ K) is produced by soft X-rays, but not sufficient to account for all the "not-strongly-absorbing" material. Some very hot, fully ionized components are discussed below. Theoretical investigations (McKee and Ostriker 1978, Cox 1978) show that the interface between an interstellar cloud and phase (3 or) 4 produces some material similar to phase 2.

Phase 3: Medium-density Strömgren spheres: The phases described above are predominantly neutral and cannot account for the mean electron density of $\bar{n}_e \sim 0.03$ cm^{-3}. Central stars of planetary nebulae and B-stars (Elmegreen 1976) could give some low-level, but widespread ionization. However, as emphasized by Mezger (1978), OB-stars contribute by far the largest amount of ionizing UV to the general ISM (see Sect. 4). With ζ_{UV} the ionizing rate per H-atom, the RMS electron density is given by

$$f^{-1} \sim \langle n_e^2 \rangle/(0.03)^2 \sim \zeta_{UV}/10^{-15}s^{-1} \qquad (1)$$

The average of 0.03 cm^{-3} can come from Stromgren spheres ($T \sim 10^4$K) with internal densities up to $n \sim 3$ cm^{-3} and filling factors as low as 0.01 (although there is some evidence for larger filling factors, Reynolds 1977).

Phase 4: Coronal gas in pressure equilibrium: Gas containing OVI is easily recongized but there could be more coronal gas at slightly higher temperatures still. It is theoretically likely that coronal gas in pressure equilibrium ($n \sim 3x10^{-3}$cm^{-3}, $T \sim 10^6$ K) has an appreciable filling factor, say $f \sim 0.2$ to 0.8.

3. MASS TURNOVER RATES

With r the rate in $M_\odot$/year for some process to flux mass through the ISM, the corresponding turnover time is $\sim r^{-1}$ ($3x10^9$ years). The ejection of planetary nebulae and the formation of white dwarfs are now both estimated (Weidemann 1978) to have $r \sim 1$. Thus, an appreciable fraction of all star deaths proceed via the planetary nebula stage. The corresponding turnover time is only a few times shorter than the present age of our Galaxy, which fits the fact that the ISM is a few powers of 2 less massive than the stars.

This contrasts with some processes which give the appearance of leading to star formation: Galactic spiral shocks set in about every 10^8 years, so that (if all parts of the ISM were affected) $r \sim 30$. Giant molecular clouds present an even bigger puzzle: A large fraction of the total mass of the ISM is in this form (Solomon 1978) and if these clouds were undergoing free gravitational collapse the turnover time would be only $\sim 10^6$ years and r would be enormously large, $r \sim 3000$. Obviously these clouds are not in gravitational collapse, but we don't know if rotation (Field 1978) magnetic pressure (Baker 1978a) or something else is balancing gravitation.

While discussing high-velocity clouds, Oort (1969) pointed out that more intermediate-velocity clouds are approaching the galactic plane than receding from it. More recent 21cm observations at high galactic latitudes have confirmed this trend for clouds and also established it for the "not-strongly-absorbing" neutral hydrogen (Dickey et al 1978b). If interpreted as net infall to the galactic plane (or fluxing through, with the outward flow ionized, the inward neutral), this velocity asymmetry corresponds to $r \sim 3$.

4. ENERGY BALANCE

Regarding the energy input into the ISM we have to distinguish sources for bulk kinetic energy from sources of photons. For photons in turn we have to distinguish between (i) "near UV" photons below the Lyman-edge, which can heat but not ionize the medium, (ii) ionizing UV photons and (iii) penetrating X-rays. I will give photon rates ζ expressed in units of $10^{-15} s^{-1}$ per H-atom. For the non-ionizing UV in HI-regions: Lyman-α is unimportant (Spitzer 1978, Draine and Salpeter 1978) but continuum stellar photons contribute $\zeta \sim 300$.

For the ionizing UV ($h\nu > 13.6$ eV), I have already mentioned "absolutely free" B-stars (Elmegreen 1976) and the lowered estimates (Pottasch et al 1978) for emission from central stars of planetary nebulae. These two sources contribute $\zeta \sim (2$ to $3)$ each to the ionizing UV, with the sources rather widely distributed. Supernova remnants contribute comparable a comparable amount of UV. There is still some slight controversy about the exact value of ζ from OB-stars: Older estimates, based on direct counts in the solar neighborhood (Terzian 1974, Torres-Peimbert et al 1974), give $\zeta \sim 25$. The average value for the whole galactic disk (including active spiral arms) should certainly be larger than the local value; working back from the observed diffuse radio-emission (both in free-free continuum and recombination lines) Mezger (1978) estimates $\zeta \sim 80$, even after allowing for the photons which are "wasted" in the dense, immediate vicinity of the star. At any rate, the uncertainty in the OB-star contribution to the general ISM is relatively small and this contribution is greater than that of any other primary source. Most of the average electron density ~ 0.03 cm^{-3} thus comes, not from a uniform phase 2, but from phase 3 with an appreciable "clumping factor" f^{-1} (see eqn. 1).

The flux of soft X-rays (100 eV $< h\nu <$ 300 eV, say) cannot compete in total ionizing rate with that of ionizing UV, but it is more penetrating and can contribute to the coexistence of neutral and ionized hydrogen which is a characteristic of phase 2. Most of the soft X-ray flux probably comes from the coronal gas in phases 4 and 4-; most of that was probably produced by supernova remnants (Jenkins 1978) and somewhat less by "blastwave bubbles" (Weaver et al 1977) from O-star stellar winds. No accurate estimates have been made to date, but $\zeta \sim 0.2$ is probably a reasonable guess for the soft X-rays (there is, in any case, no sharp dividing line between UV and X-rays).

As a primary source of the bulk kinetic energy, required for "stirring" the interstellar clouds, I am particularly fond of blastwaves produced by supernova remnants (Salpeter 1976). The dynamics is complicated because of the inhomogeneity of the ISM (Cox 1978), McKee and Ostriker 1978, Spitzer 1978), but $\sim 10^{-14}$ eV s^{-1} (per H-atom) is a reasonable estimate. Qualitatively, at least, the observational evidence for large-scale effects of supernova remnants is compelling (Weaver 1978). "Blastwave bubbles" (Weaver et al 1977) are also blown by stellar winds emanating from O-stars at speeds exceeding 1000 km s^{-1}. They have qualitatively similar effects to those of supernova remnants, but I estimate their total energy input to be somewhat lower, probably by a factor of about 2 to 10. The stirring rate required to keep up the velocity dispersion of interstellar clouds against "cloud-cloud collisions" is somewhat uncertain because hydromagnetic phenomena and magnetic fields affect the "collision cross section" of a cloud in an unknown way (Spitzer 1978). The estimate for this dissipation rate is $3 \times 10^{-15 \pm 1}$ eV s^{-1}, which comfortably overlaps the (also rather uncertain) above production rate from supernova remnants.

Regarding the temperature balance between heating and cooling, the situation is fairly clear for most of the components: The heating is maintained by the grain photoeffect and by carbon ionization for phase 1 and by hydrogen ionization for phase 3. Phase 4 material was originally heated by shocks and in any case cools rather slowly. Only the "warm, neutral intercloud medium" with $\bar{n} \sim 0.2$ cm^{-3} seems to present a problem in the sense that no <u>single</u> heat source can provide sufficient heating for all this material:

I hope that this puzzle will be solved by the fact that a number of very different heat-sources are at work and that the "intercloud medium" is itself a composite: As discussed in Sect. 2, some part is contributed by "phase 2" where neutral gas in some fraction of the ISM is kept at a few thousand degrees by soft X-rays from some nearby source. Some part is contributed by "phase 2-", neutral material at the edge of a cloud which is heated by thermal electron conduction from phase 3 to 4 (McKee and Ostriker 1978). The exact amount of this contribution is uncertain (partly because plasma oscillations and magnetic fields make the conduction coefficient uncertain), but it certainly helps raise the harmonic mean temperature of a cloud. Finally, a number of heat sources contribute to interstellar clouds, especially to the "substandard clouds" represented by "phase 1+":

Besides the heating produced by the ionization of carbon-atoms, heating by the photoejection of electrons from grains (using the "near UV" stellar emission) is quite important (Watson 1972, Jura 1976, deJong 1977, Draine 1978). Furthermore, the bulk kinetic energy provided by the "stirring rate" I discussed above is transformed into heat via shockwaves or hydromagnetic waves (Cesarsky 1975, Silk 1975) produced by "cloud-cloud collisions". The actual temperature reached is somewhat history-dependent because molecular hydrogen, if present, is an efficient cooling agent.

I finally return to scaling arguments for giant molecular cloud complexes which, as mentioned, cannot normally be under gravitational collapse: This fact is particularly striking in the 5 kpc "molecular ring" where these complexes make up most of the mass of the ISM and densities and luminosities are enhanced. Essentially, one such complex is more like a "mini-galactic-disk" than like a single, unstable cloud. Luminosity L and gas mass M are both high there and controversy exists (Mezger 1978, Puget et al 1978) whether $\zeta \propto L/M$ is the same there as in our "local disk" or slightly larger. However, for most aspects of the heating-cooling balance it is not ζ which counts but ζ/n. Whether ζ is up slightly or not, the density n is certainly up by an enormous factor in one of these "mini-galactic-disks" and cooling must certainly have the upper hand over heating!

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DISCUSSION

Verschuur: The absence in the symposium of a major paper on magnetic fields is regrettable. This may reflect the complexity of the field data and its interpretation. We should bear in mind that supernovae may act to destroy spiral structures. In some of the photos of other galaxies we have seen so far one often notices complete disruption of an arm somewhere along its length and in some cases arms simply terminate within the Galaxy. Magnetic field data may be very important in helping us understand what forces capable of destroying spiral arms are operating. Perhaps by recognizing the disruptive influences, and the disrupted regions, we might be able to derive a clearer view of the underlying "grand design".

Kerr: The lack of direct discussion on magnetic fields is partly due to the fact that the intended speaker on this subject was unable to come, and partly because many of the things we know about them are not "large-scale".

Baker: I should like to comment on the high rate of fragmentation and collapse in magnetically supported clouds as derived by Langer (preprint) and by Nakano (PASJ 28, 355; 29, 197). Both assume that the coupling of field and gas is due solely to ions. As these are rare, their rates are high. The coupling is actually dominated by dust grains (Baker, A.&A. 50, 327) which are charged by electron collisions (Spitzer, Ap. J. 93, 369). The rate remains significant but must compete with turbulent diffusion which homogenizes field and gas. Thus a quiescent cloud might be unstable on a timescale of 10^7 years, but not clouds of the sort which we actually observe.