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Hydrogen Flash in Stars

DURING the past few years there has been some progress in understanding the way in which a star approaches the main sequence. In their studies of the pre-main sequence evolution of stars, Ezer and Cameron[1] assumed that the stellar material started with the highest possible adiabat consistent with the virial theorem (for a given temperature a high adiabat has a low density and a low adiabat has a high density). In later hydrodynamic collapse studies of the formation of a star with zero angular momentum, Hayashi[2] and Larson[3] showed that much of the internal energy of the collapsing gas is radiated away, so that the stellar material must start on a much lower adiabat. The gas in the centre of such an object can only be heated by compression, so that it remains on a low adiabat. As the outer layers of the star fall onto this core, they undergo shock heating, due to gravitational potential energy release, which raises their adiabat, and allows the star to form a stable body in hydrostatic equilibrium prior to reaching the main sequence.

It is unrealistic to expect a star to form with zero angular momentum. Star formation studies[4] have shown that collapsing interstellar gas should form a flat disk, from which the star should form by gaseous dissipation processes[5]. The gas density near the disk centre is comparable to that in the collapsing core of Larson's models at which the first halt and mild shock heating occurs[3]. Hence shock heating effects should be relatively unimportant when a flat rotating disk (primitive solar nebula) is formed. The initial low adiabat of the gas in the disk will not be raised during the dissipation, but is likely to be substantially lowered as a result of radiation into space from the photosphere[5].

We have estimated the initial adiabat of the gas in the disk in several ways. Collapsing interstellar gas undergoes isothermal compression with a temperature of about 10 K as long as the emitted radiation is free to escape from the system[2,3]. When the density becomes high enough, the subsequent compression is adiabatic, but there is an ambiguity concerning the adiabat, because we do not know the distribution of the hydrogen molecules between the para and ortho forms[6]. We have used Larson's estimate of the temperature and density at which the switch from isothermal to adiabatic compression begins, and have computed the adiabat based on two possible limits in the relative number of parahydrogen and orthohydrogen molecules.

A third estimate is based on the pressure and temperature conditions deduced for the primitive solar nebula at the time of meteorite accumulation. Accumulation processes should take place rapidly in the primitive solar nebula[4], so that the thermodynamic conditions associated with accumulation probably differ rather little from those in the initial nebula. Although there is still considerable uncertainty associated with the meteoritic cosmothermometers and cosmobarometers[7–10], we can take approximately a temperature of 450 K and a pressure of 5×10^{-6} atmos as the conditions defining the adiabat.

We extended these adiabats toward higher temperatures and densities, taking into account the internal energy of excitation of hydrogen molecules, and the dissociation and ionization of hydrogen and helium. Because the adiabats are relatively low, thermal dissociation of hydrogen molecules is not complete before effects of pressure dissociation become important; we have estimated the lowering of the dissociation energy at higher pressures following Vardya[11]. The subsequent thermal ionization of the hydrogen atoms is very inefficient; more than half of the hydrogen atoms remain neutral until pressure ionization takes place. At higher densities the ionization energy of hydrogen is lowered through coulomb binding of electrons to the plasma[12], but pressure ionization results chiefly from the partial shielding of the K-shell electrons in the neutral atoms by free electrons inside the classical Bohr radius[13]. The final adiabat is relatively insensitive to crude approximations in this treatment.

After ionization is complete, the adiabat can be written in the conventional form $P = K\rho^{5/3}$. With the pressure and density expressed in c.g.s. units, we found for our three estimates of the initial adiabat, $K = 1.08 \times 10^{13}$, 1.67×10^{13} and 2.61×10^{13}. The first two of these values correspond to the Larson estimate for the onset of adiabatic compression, the first when hydrogen molecules are all in the parahydrogen form, and the second when the para/ortho ratio is 1/3. The third value corresponds to meteoritic accumulation conditions. Because it represents the highest adiabat, our subsequent discussion is based on this third value.

We consider a star which has this initial adiabat everywhere in its interior structure. Such a star can be represented[14] by a polytrope of index 1.5. The central conditions are determined through specification of the total mass M and the adiabatic constant K. For the centre of such a polytrope we find a temperature of 7.0×10^7 K and a density of 7,200 g cm $^{-3}$. These values are much higher than now exist at the centre of the Sun. For the present central solar temperature of 1.5×10^7 K, the density on the adiabat is 700 g cm^{-3}, also much higher than the present central density of the Sun. Further lowering of the adiabat by radiative cooling would increase these discrepancies.

So the Sun is unlikely to have formed as a spherically-symmetric body in hydrostatic equilibrium before the onset of hydrogen-burning at the centre. The ignition of hydrogen thermonuclear reactions evidently took place while the central portion of the solar nebula still formed a flattened rotating disk. The nuclear energy released during a possible preceding phase of deuterium burning is too small to modify this conclusion. If we take the D/H ratio in the solar nebula to be 10% of that in the oceans, the density at a given temperature would only be decreased by about 30% during the deuterium-burning process. The dissipation processes leading to the hydrogen ignition should take only a few thousand years[5].

It is a property of a self-gravitating infinite plane distribution of matter that the pressure at the central plane is independent of the temperature[5]. This resembles the situation in an electron-degenerate stellar core. Thus it is possible that the ignition of hydrogen-burning reactions at the centre of the disk can be accompanied by a thermal runaway. This is likely to raise the adiabat of the gas to a higher value than it would attain on the main sequence, expanding the star and forming a body in hydrostatic equilibrium somewhat on the low temperature side of the main sequence in the Hertzsprung-Russell diagram. There would be a rapid rise in the luminosity at this time. This process may explain the sudden flare-up of the star FU Orionis[15].

The process may also account for hitherto puzzling features of the Hertzsprung–Russell diagrams of young clusters. In such clusters the lower luminosity stars are displaced somewhat to the low temperature side of the main sequence. Even the very low luminosity stars are remarkably close to the main sequence; this has seemed to require that they formed many millions of years prior to the higher mass stars[16,17]. But the dissipation times in flat rotating disks having a wide range of masses are probably all comparable to a few thousand years, less than the dispersion in the interstellar collapse times, and the hydrogen flash process then places the resulting stars all quite close to the main sequence.

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Depositional Histories of Sand Grains from Surface Textures

THE use of the electron microscope to determine the depositional histories of sand grains is a relatively new but well acclaimed technique[1-6]. The underlying principle is that a detrital quartz grain will bear surface textures that may be related to processes that have operated on it during transportation and deposition.

In 1968 Krinsley and Donahue[4] published micrographs with very full descriptions intended as a glossary of submicrographic sand surface textures. Littoral (beach), aeolian (dune), glacial and diagenetic textures were outlined based on the work of 8 years involving more than 400 sand samples and 4,000 grains. Where possible laboratory duplication of textures was carried out. Krinsley and Donahue stressed the importance that an assemblage of textures should characterize any one abrasive process—a single texture cannot be considered completely diagnostic. An attempt was also made to relate the textures observed to the mechanical or chemical process involved.

I do not intend to undermine the valuable work of Krinsley and Donahue[4], but suggest here some possible reservations in the interpretation of sand grain surface textures.

During the course of an investigation by scanning electron microscope of some Pleistocene sands of controversial origin from NE Cheshire, sand samples were also selected from known environments to act as standards for comparison with the Pleistocene sands. Among these were quartz grains of primary origin from freshly weathered granite in Northumberland and collected from a stream which drained only the granite; beach sands from Studland Heath in Dorset, eroded from Cretaceous Lower Greensand; and freshly weathered Carboniferous Millstone Grit grains from the Goyt River valley, Derbyshire. Carboniferous sandstones are believed to be the principal source rocks of the Pleistocene sands[7]. Because all the standard samples, except the beach sands, were freshly weathered, and the beach sands were collected from an area devoid of glacial deposits, there should have been no indication of glacial abrasion. But the surfaces of very many of these grains frequently show textures closely resembling those described as glacial[4]. Fig. 1 is a micrograph of a primary quartz grain from the Northumberland granite, showing high angularity, high relief and arcuate, semi-parallel fractures. Fig. 2 shows a freshly weathered Millstone Grit grain; the same features are clearly visible. Fig. 3, a micrograph of part of the surface of a quartz grain collected from the beach at Studland Heath, Dorset, shows an arcuate, parallel fracture pattern, with rounding of the fracture probably the result of marine abrasion. A similar feature on a quartz grain from a subantarctic deep sea core has been described by Margolis and Kennett[8] as being produced in a glacial environment and suffering subsequent rounding in an aqueous environment.

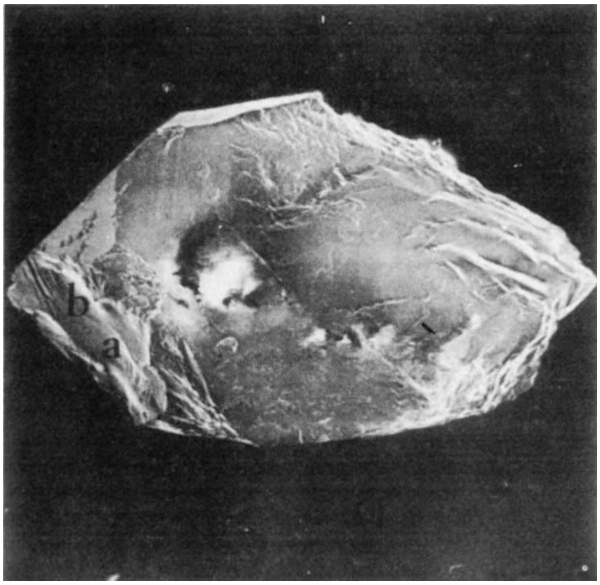

Fig. 1 Micrograph of a quartz grain freshly weathered from Cheviot granite, Northumberland. The grain shows high angularity, fairly high surface relief and both arcuate (a) and parallel (b) fracture patterns. (×56.)

It thus seems possible that features described as glacial by the earlier criteria[4] may be found on grains from a variety of environments and which have suffered no glaciation.

Krinsley and Margolis[5] stated (with reference to aeolian surface textures): "The meandering pattern results from the intersection of slightly curved conchoidal breakage patterns; the conchoidal pattern is probably caused by grain to grain collision in an aeolian medium. These breakage patterns differ from their glacial counterparts in that they are smaller than the largest glacial breakage pattern and have greater uniformity; they differ from those produced by beach action in that the area enclosed is somewhat rounded and more uniform."

There is no real indication here how to distinguish between small glacial fractures and aeolian fractures. Similarly it is probable that a fracture of any origin will tend to become rounded and the area enclosed uniform if subjected to a period of aqueous abrasion.

Krinsley and Margolis[5] have related the characteristic glacial features of angularity, high relief and large variation in the size of arcuate breakage patterns to the equally large