SOLAR GRAVITY WAVES: CAUSE OF TERRESTRIAL ICE AGES

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Summary

Gravity waves cause the solar interior to mix approximately every 250 million years. The mixing throws the sun out of thermal equilibrium for about 10 million years, decreasing the solar neutrino flux and reducing the solar luminosity. This mechanism resolves current debate on the validity of solar models and provides a plausible explanation for the ice ages.

One of the earliest and most obvious apparent successes of the theory of stellar structure and evolution is the explanation of the main sequence. Theoretical models of main sequence stars can be constructed with surface boundary conditions that agree so closely with observations that until recently few people have questioned seriously how well they represent real stars beneath the surface. In particular, the sun, which is a quite typical main sequence star, has been considered well understood at least in broad outline.[1]

A question that has intrigued geophysicists for more than a century and a half is why the earth has suffered periods of increased glaciation, or ice ages. An early hypothesis was that ice ages resulted from a temporary reduction in the solar luminosity.[2] From the climatological point of view this common-sense idea is still perhaps the most attractive,[3] but it is not consistent with modern solar models. Consequently the idea has not been taken seriously in recent years. Indeed, according to stellar evolution theory the sun's luminosity has been monotonically and approximately exponentially increasing with time since nuclear fusion became the principal energy source 4.7×10^9 years ago.

Many alternative theories of ice ages, most of which invoke causes intrinsic to the earth itself, have been advanced in the last few decades. Each one, however, is either incomplete as an explanation or conflicts with geological data. Most seem to be primarily concerned with the quaternary ice age and none of them satisfactorily accounts for the sequence of precambrian glaciations.

Any acceptable theory of ice ages must explain the time interval between major glacial periods. The geological evidence suggests that for the last 1.5×10^9 years or so this interval was approximately 2.5×10^8 years, and not strictly constant;[4] poor time resolution in the data does not permit a confident estimate of its value at earlier times. There is no obviously relevant recurrent phenomenon on Earth with a timescale known to correspond to this value. That is one reason why purely terrestrial ice age theories have failed. However, the inter-ice-age interval is about the same as the time required for a significant chemical inhomogeneity to be built up by nuclear transmutations in the core of the sun, provided the solar interior is not mixed. This is a clue that leads one to suspect that variations in the solar energy production, arising perhaps from an instability in the core, might indeed be the cause of the ice ages.

A second clue can be found in Davis' attempt to detect solar neutrinos.[5] Provided the relevant nuclear physics is correct, this has imposed a constraint on the sun's structure which seems to imply that the nuclear reactions in the solar core are too slow to generate the energy necessary to maintain the surface luminosity at its present value: either the nuclear reaction rates, or the luminosity, or both must have changed in the last 10^7 years, the thermal diffusion time for the sun.

One is led, therefore, to question theoretical models of the sun. Has the sun been evolving monotonically up the main sequence, as is generally believed, or has it suffered periods of instability which caused its luminosity to fluctuate?

The criterion adopted by Schwarzschild[6] for instability to infinitesimal direct convective perturbations, namely that the temperature gradient be superadiabatic,[7] is the sole criterion used to test the stability of chemically homogeneous regions of solar models. Near the centre of the sun the conditions under which the criterion is valid are not satisfied, partly because a gradient in composition may have built up and partly because there is an internal thermal energy source. Because there is a large discrepancy between the timescales appropriate to convection and to thermonuclear energy generation, the correction which must be made to the criterion for instability to direct modes is negligible. However, chemical inhomogeneity does modify the marginal stability criterion, and under some circumstances might permit instabilities of finite amplitude. Nuclear reactions generate composition gradients in such a direction as to increase stability to infinitesimal convection, so it is generally concluded that if the Schwarzschild criterion is not satisfied convection is not possible at all. In no part of the inner two-thirds (by radius) of solar models that represent the sun at the present epoch is the Schwarzschild criterion satisfied. For this reason it is generally concluded that the deep interior of the sun is stable.

However, low amplitude convection is not the only direct means by which a star might initially become unstable. Stationary acoustic waves cause the variability of Cepheid and RR Lyrae stars, for example, but there are good reasons, both observational and theoretical, for believing that such modes would be damped in the sun. It has been pointed out recently,[8] however, that conditions in the sun might sometimes be ripe for exciting stationary gravity waves, and that these in turn might trigger finite amplitude convection.

Gravity waves can be generated in stratified fluids that are convectively stable. Their existence depends on an inbalance between gravitational forces and pressure gradients which creates a restoring buoyancy force when an element of fluid is displaced vertically from its equilibrium position. The growth or decay of such waves can be understood by considering the temperature perturbations they induce in the fluid - in this case a nondegenerate gas. When there is no thermal energy source, conduction and radiation act to smooth out the temperature perturbations, and therefore damp the gravity wave. However, a temperature dependent thermal energy source in the fluid can act to augment the temperature perturbations; and if this more than compensates for the conductive and radiative losses the gravity wave will grow. In other words, gravity waves can be destabilized by thermonuclear reactions if the energy generation rate increases sufficiently rapidly with temperature.

The Schwarzschild criterion is local. The criterion for the stability of gravity waves is not, because gravity waves propagate. Even stationary gravity waves cannot be confined to the core and damping in the envelope opposes driving in the core. The zero-age homogeneous solar model is stable. Mixing in the core does not occur and a composition gradient results from the nuclear reactions. But as the star evolves, a downward displaced fluid element becomes richer in nuclear fuel than its surroundings, by an amount proportional to the composition gradient, and the fluctuation in the energy generation rate increases. Dilke and Gough[8] estimate that after about 10^9 years the gradient is sufficient to excite gravity waves and so destabilize the sun.

Once gravity waves are excited, Dilke and Gough argue, transient finite amplitude convection is triggered which mixes extra hydrogen into the central regions. If nuclear reactions cannot maintain the luminosity of a star, the star contracts and heats up, drawing upon its gravitational energy. Conversely, the excessive thermonuclear energy liberated in the mixed solar core causes the sun to expand and cool on a timescale of 10^6 years, the thermal diffusion time for the core. The surface luminosity falls by about five per cent and the solar envelope, now on average further from the centre and in a weaker gravitational field, exerts a lower pressure on the core. The consequent expansion and cooling of the core causes the nuclear reactions to slow down temporarily to less than their normal rates. It takes about 10^7 years (the thermal diffusion time for the entire sun) for thermal balance to be restored, and a shorter time for convection in the core to die down. The mixed core no longer supports a composition gradient to excite the gravity waves and the sun must wait another 10^9 years before the process is repeated. If quaternary glaciation was initiated by such a process just two or three million years ago, it follows that the sun is out of thermal balance now, sufficiently so in fact to explain Davis' low neutrino counts.

The criterion for gravity wave instability has so far been inferred only from a simplified solar model; the coincidence between the measured intervals separating major ice ages and the calculated intervals separating solar mixing phases is therefore close enough to be encouraging.

The theory must be developed much further before it can be convincing. First, it must be established whether more realistic solar models are unstable to stationary gravity waves. Second, the finite amplitude convective instability must be studied in greater detail. Third, it must be demonstrated that the unstable gravity waves can indeed trigger finite amplitude convection; the only argument supporting this at the moment is an analogy with similar but different physical systems.

What of the response of the earth itself? Unless the gravitational constant has been decreasing with time, the solar luminosity has, on the whole, been increasing. If ice ages were the equilibrium climate at an insolation five per cent below the present value, as some modern calculations might lead us to believe,[9] the earth would have been continuously glaciated until about 10^9 years ago. Ice ages must therefore be a transient response. Only if there is a climatic process with a characteristic timescale at least as great as 10^6 years can this be possible. Tertiary temperature oscillations both on land[10] and in the oceans[11] with such long periods have been observed, but no-one knows what might have caused them. Meteorologists and climatologists are still far from understanding the delicate and complicated balance of our ergosphere. We do not even know whether the extent of the present glaciation will continue to oscillate or whether we are at last emerging from the present ice age. Dilke and Gough predict that before the sun regains its thermal equilibrium it will, in two or three million years time, become more luminous than usual. So perhaps for a while the climate will become exceptionally hot, but we shall not be here to witness it.

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Fisher Dilke was born in London in 1948. He obtained his B. Sc. degree from Sussex University in 1969, and is currently studying for his Ph. D. degree at the University of Cambridge.

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