The law-abiding Universe

The second law of thermodynamics demands that the entropy of any closed macroscopic system should never decrease. The laws of physics naturally drive systems towards states of increasing disorder and thermal equilibrium, as we all know. Yet these basic precepts, when applied to the Universe as a whole, meet with an apparent paradox. The Universe, cosmologists believe on strong evidence, existed some 13 billion years ago in a hot, dense phase of remarkable uniformity; that is, in a homogeneous condition akin to thermal equilibrium. Since that time it has expanded and cooled, and the matter and energy within has condensed into a rich variety of ordered forms ranging from stars to living and thinking human beings. Now, evidently, the Universe is very much out of thermal equilibrium; its entropy has apparently decreased.

What's going on? In particular, if the Universe was once in equilibrium, how has it got so far away from it? The consensus seems to be that the resolution of this paradox has everything to do with gravity, and possibly with the peculiar nature of black holes, which carry enormous amounts of entropy and exist in abundance now, but didn't in the early Universe. Is this true? Perhaps. But it also seems that the applicability of notions such as entropy, thermodynamics and equilibrium becomes anything but clear when gravity enters the picture; consequently, this is an area where good science can be done merely by efforts to clarify fundamental issues, which David Wallace of Oxford University has recently tried to do (http://arxiv.org/abs/0907.0659; 2009). The argument that gravity is the key, Wallace suggests, seems to be correct, although persisting confusions often plague discussions of the matter.

The process of 'taking gravity into account', he points out, means two very different things. It means considering the field itself — which determines the spacetime metric — as a dynamical entity that has its own entropy. It also means including the field's influence on the dynamics of particles. The former effect is clearly of paramount importance in black holes, which possess enormous entropy tangled up in their internal field configurations.

Some physicists see this as the primary explanation of how entropy has increased

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even as the Universe seems to have developed more order. But this, Wallace suggests, can't really be the answer, because the problem remains of how most of the bulk of the Universe — for which Newtonian gravitation offers an adequate description — has similarly gained apparent order. Hence, the nature of the paradox seems to depend on 'taking gravity into account' in the second sense, through its influence on the dynamics of physical systems. Understanding this properly, it turns out, is not so easy.

Our intuitions about entropy mostly come from experience with systems having short-range interactions. Take a dilute gas, for example. In general, the entropy of such a system goes up if it gains more volume or kinetic energy, both of which increase the number of accessible states in phase space. For fixed volume and energy, the highest entropy state is always spatially uniform. Most of us have come to expect that uniformity is always a property of thermal equilibrium.

But the long-range interactions of gravity (which are never screened in the way electromagnetic interactions generally are) introduce something new, as they inevitably work against uniformity, and tend to concentrate matter over time. As a popular argument goes, gravity increases the kinetic energy and hence the temperature of the matter as it condenses, and in a way that overcompensates for the loss of entropy from clumping. Hence, although matter and energy in the early Universe may have been distributed uniformly, it was very much not in thermal equilibrium, and gravity could still drive the system towards non-uniform but higher entropy states.

But this kind of story — although it sounds plausible — needs fleshing out. As Wallace notes, one can easily come up with examples of concentrated matter with either higher or lower entropy than the same matter in a diffuse state (the balance can be shifted simply by heating up either one). So whether concentration really increases entropy clearly depends on the nature of the dynamical process. To test the claim that gravitational clumping should increase entropy, Wallace calculates the effect for a trivial model of an ideal gas, and finds that the entropy on contraction should generally either decrease or increase marginally, depending on the overall energy of the particles. This result indicates that the scenario of entropy-through-collapse isn't as straightforward as it sounds.

However, it turns out that the thermodynamics of gravitating systems is actually far more bizarre than one might anticipate. For example, astrophysicists have come to recognize that gravitating systems can have a negative heat capacity and so increase their temperature on the emission of heat. The effect seems to be relevant in both stars and star clusters, and depends on a simple dynamic. If a gravitationally bound system has overall negative energy, and loses some heat to the external world, its energy only becomes more negative and its components more strongly bound. One can show that this leads to an increase in the average kinetic energy of the constituent particles; the temperature increases.

It turns out, as a consequence, that a uniform cloud of gravitating particles won't stay that way, but will generally collapse progressively into a dense core and an ever more diffuse envelope in a process known as gravi-thermal catastrophe. This implies that gravitational collapse can indeed increase entropy, and our intuitions in this area simply fail us. Gravity-dominated systems just do not have equilibrium states, but tend to collapse (at least in their cores) while emitting heat and simultaneously growing hotter until some other influence acts to resist gravity. In the case of stars, this influence is the internal pressure generated by nuclear fusion.

All of which helps clarify, for me at least, how the evolution of the Universe is indeed consistent with the second law. Thinking about thermodynamics and the nature of equilibrium just isn't straightforward when gravity is involved. We may think the familiar principles of thermodynamics apply to all macroscopic things, but do they really? The answer, as one physicist puts it, "is unexpectedly unclear". ❐

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