Does the Collapse of a Gas Cloud to Form a Star Violate the Second Law of Thermodynamics?

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Abstract

I propose that the answer to the title question is "no." I show that the change in entropy of a self-gravitating gas cloud as it contracts is negative. This general result is applied to the specific cases of a contracting pre-stellar cloud and to the Kelvin-Helmholtz mechanism. However, I argue that this does not violate the second law of thermodynamics, because both processes involve heat losses. By definition, a heat loss has a negative entropy change. In any heat transfer problem it is necessary to consider both the emission and absorption of heat in calculating the total entropy change to properly evaluate whether the process violates the second law of thermodynamics. Thus it appears that the theoretical contraction of a gas cloud to form a star does not violate the second law of thermodynamics. It is recommended that creationists do not use this argument to critique the theory of stellar evolution. However, there remains a long-standing problem with how the alleged initial contraction of a gas cloud can commence. This is a valid criticism of star formation.

Introduction

In a classic *Creation Research Society Quarterly* article Mulfinger (1970) detailed a number of objections to the theories of stellar evolution. Some discussion was given to the collapse of a gas cloud to become a star. This theoretical stage of a star's development is called the pre-stellar phase of stellar evolution (a recent non-creationist treatment of star formation is that of Phillips, 1994). Using parameters of the collapsing gas cloud (size, density, temperature, etc.) taken from the astronomical literature and a thermodynamic relation, Mulfinger showed that the entropy of the cloud would decrease as it collapsed. Because this appears to violate the second law of thermodynamics, Mulfinger concluded that the process is impossible.

In the ensuing years speakers have often referred to this calculation to argue that stellar evolution is impossible. I recently challenged this assessment (Faulkner, 1998). A more detailed reevaluation of the entropy calculation and its meaning are presented in this paper. It will be argued that when all factors are considered the overall change in entropy is positive, in agreement with the second law of thermodynamics. This is not to be construed as an endorsement of the theory of pre-stellar collapse, for there is another devastating problem that Mulfinger noted and which will be discussed briefly here as well.

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Calculation of Entropy Change

While Mulfinger's calculation of the entropy change of a collapsing gas cloud is approximately correct, Mulfinger unfortunately did not consider the total entropy change of the universe. Ultimately the temperature of space is about 2.7K, quite a bit cooler than any gas cloud. To a very good approximation space represents a 2.7K thermal reservoir that completely surrounds the cloud in question. Therefore a gas cloud and surrounding space define a thermodynamic system in which heat flow can be analyzed. In this fashion all gas clouds are capable of losing energy to space.

First, let us examine Mulfinger's calculation of the entropy change of the collapsing gas cloud. Assume that the gas in the cloud can be adequately described by an ideal gas and that the cloud represents a thermodynamic system. Let T be the temperature of the thermodynamic system and let dQ be the heat flow into the system. Note that heat flow into the system is defined to be positive, while heat flow out of the system is negative. A heat flow is accompanied by a change of entropy dS, defined as

$$dS = dQ/T. \qquad (1)$$

Mulfinger attempted a detailed calculation by using a relation derived from the first law of thermodynamics:

$$dQ = dU + dW, \qquad (2)$$

where dU is the change in internal energy and dW is the work done by the gas. The work can be expressed in terms of the change in volume as the gas cloud collapses. The internal energy usually can be expressed as the product of

C_V, the specific heat at constant volume, and the temperature. Since the specific heat is a constant, the change in internal energy can be written as the product of the specific heat and the change in temperature. In a footnote Mulfinger argued for the replacement of C_P for C_V, because the volume of the collapsing cloud is not constant, while the ambient pressure is. This is incorrect; C_V should be used. It is easy to understand the confusion on this point, because the volume does change tremendously, but the pressure remains virtually constant in this stage of alleged evolution. However, recall that the C_V term in this equation is from the change in internal energy ($dU = C_V\, dT$), not because it represents heat flow. In either case, whether C_V or C_P is used, the result will be the same as will be shown shortly.

The relation resulting from these substitutions (Mulfinger's equation 1) can be found in any thermodynamics text. This equation works well in the lab, but cannot be used in this case, however, because the cloud has enough mass for gravity also to be important. Hence the potential energy must include a term involving gravitational potential energy. Properly writing the gravitational potential energy requires knowledge of the cloud's density structure. This structure is a function of distance from the center, which makes the correct entropy calculation more complicated than Mulfinger assumed.

Assuming a polytropic model for the gas cloud probably can best solve the problem. On the other hand, if one desires merely the sign of the entropy change rather than a numerical value of the entropy, the problem can be solved very simply. As the cloud collapses, gravitational potential energy is released which partly heats the gas and partly is radiated away. By the virial theorem the change in gravitational potential energy is evenly split between the two (Clayton, 1968). The heat radiated away is a heat flow, and it would be represented by dQ in equations 1 and 2. Because dQ is a heat loss, its sign must be negative, and since temperature is always positive, dQ/T must be negative at all times for the collapsing cloud. Thus integration of equation 1 will always produce a negative answer. This qualitative assessment agrees with the quantitative result of Mulfinger. Does this violate the second law of thermodynamics? No, as the following example will illustrate.

Let us apply Mulfinger's approach to the Kelvin-Helmholtz contraction as the mechanism to power the sun. A century ago, before the discovery of modern physics, this was considered to be the source of the sun's energy. For the evolutionist, the Kelvin-Helmholtz theory is untenable, because it could only operate over a few tens of millions of years instead of the billions thought necessary. Many recent creationists reject thermonuclear reactions as the source of the sun's energy, concluding that the sun is powered by this mechanism instead (Hinderliter, 1983 [note: while Hinderliter is no longer a recent creationist and would now disavow this paper, he was a recent creationist when he wrote the paper, and this is a commonly quoted source on this matter]; Davies, 1996). The sun is a spherical cloud of gas, so its gravitational potential energy in proportional form is given by:

$$U_g \propto 1/r, \tag{3}$$

where r is the radius of the sphere. Taking the differential,

$$dU_g \propto dr/r^2. \tag{4}$$

From the virial theorem, half the liberated gravitational potential energy heats the gas, while the other half is radiated. Therefore the change in thermal energy

$$dU_T \propto dU_g. \tag{5}$$

Notice that even if the virial theorem only approximately holds, the above proportionality is still valid. For an ideal gas the change in thermal energy is proportional to the change in temperature, from which we conclude

$$dT \propto dU_T \propto dU_g \propto dr/r^2. \tag{6}$$

Inspection reveals that

$$T \propto 1/r. \tag{7}$$

With this, Mulfinger's equation 2 can be written

$$dS = C_P \ln(T_2/T_1) + R\ln(V_2/V_1), \tag{8}$$

where S is the entropy, C_P is the specific heat at constant pressure, R is the ideal gas constant, and T and V are the temperatures and volumes at two different times subscripted in order as 1 and 2. Since $C_P = 5/2\ R$, $T \propto 1/r$, and $V \propto r^3$ we find that:

$$dS = -5/2\ R\ln(r_2/r_1) + 3R\ln(r_2/r_1) \text{ and} \tag{9}$$

$$dS = ½ \ln(r_2/r_1). \tag{10}$$

Because the sphere of gas is contracting, $r_2 < r_1$, so that $\Delta S < 0$. Earlier it was argued that C_V should have been used rather than C_P. Either way the result is not changed, because $C_V = 3/2\ R$, and use of that value makes dS even more negative.

Thus using Mulfinger's approach one would conclude that the Kelvin-Helmholtz mechanism violates the second law of thermodynamics. No one doubts that the Kelvin-Helmholtz mechanism could explain the sun's luminosity on the time scale of thousands of years. Indeed, as mentioned before, this is the preferred mechanism of some recent creationists. The fact that Lord Kelvin was the codiscoverer of this model of possible solar energy generation as well as perhaps the most influential person in the development of thermodynamics should cause us to question the conclusion that the Kelvin-Helmholtz mechanism violates the second law. Thus we are forced to consider the possibility that the approach used by Mulfinger to show that the contraction of a self-gravitating gas cloud to form a star violates the second law of thermodynamics is itself flawed.

Virtually all thermodynamics textbooks ignore the affects of gravitational potential energy, or suggest that any changes be accounted for separately from changes in the internal energy of the gas and any work performed on or by the gas. The reason for this is that in the relatively small parcels of gas in nearly all situations envisioned and treated in the textbooks, the amount of gas is far too small to have self-gravity. The only gravity in these situations would be the force of gravity due to the earth, the energy of which has the form mgh. Changing the altitude of the gas does not have a direct effect upon the internal energy of the gas. Thus any changes in gravitational potential energy in this circumstance would be separable from the other energy terms.

In the case of a self-gravitating cloud, the internal energy due to self-gravity cannot be ignored. What would be the result if the internal energy were properly written to include gravitational potential energy? From equation 3 the gravitational potential energy varies as 1/r. To be included in equation 8 it must be expressed as dU_g/T. From equation 6,

$$dU_g/T \propto dT/T. \qquad (11)$$

Integration as before yields $\ln(T_2/T_1)$, which is positive because $T_2 > T_1$. The question is if this positive term is greater than the negative term of equation (10). Because equation 11 is a proportionality, it lacks the units of equations 8, 9, and 10. Conversion to the molar values of those three equations would require a model of the density structure of the cloud. This greatly complicates the problem, and the result would be subject to the criticism that it is model specific. However, there is a strong argument that when this term is evaluated, the resultant entropy change will still be negative. That argument will now be pursued.

Consideration of Heat Flow

What is the physical reason for the negative entropy change calculated from equation 10? Recall that entropy change is defined to be the heat flow divided by the temperature (equation 1). Since all temperatures are greater than zero, all heat losses cause negative entropy changes and all energy gains represent entropy increases. When looking at equations such as 8 and 9 it is very easy to lose sight of that fact. As the cloud contracts it liberates gravitational potential energy, which must go somewhere. The virial theorem dictates that half the liberated energy goes into heating the gas, and the other half is radiated away. This latter term represents a heat loss, which by equation 1 must be negative. So it is not surprising that a self-gravitating contracting cloud experiences a negative entropy change. To do otherwise would require that the cloud would hoard all of the released gravitational potential energy plus absorb energy from an external source.

Does a self-gravitating and radiating cloud violate the second law of thermodynamics? Not any more than any object that cools by radiation. Consider a cup of hot coffee that is allowed to cool slowly in a room. The heat flow out of the coffee is negative and so its entropy change, dS_1, by equation 1 must be negative. This sort of process is observed every day, so it must not violate the second law of thermodynamics. How is this resolved? The surroundings (the room and its contents) absorb all of the energy lost by the cup of coffee. The immediate environment is also a thermodynamic system, and the heat that it absorbs is a positive heat flow that results in a positive entropy change, dS_2. Because the temperature of the environment is less than the temperature of the coffee, $|dS_2| > |dS_1|$. If the cup of coffee and its environment are combined into a single system, the total change in entropy, $dS = dS_1 + dS_2$, is positive. Indeed, the whole point of entropy is that it indicates the direction is which processes proceed. The coffee, because it is warmer, must shed heat to its surrounding. Entropy is defined so that it ensures that heat never flows "uphill," against a temperature gradient.

In the same fashion it should not be surprising that the entropy of a collapsing pre-stellar cloud when it is considered alone decreases. But this is only half the story: the interstellar environment at a temperature much lower than the cloud's temperature absorbs the energy radiated by the cloud. Early in the process much of the energy will be radiated at long wavelengths. If the local environment is sufficiently dusty, some of the radiated energy will be absorbed locally, but much of it could escape to great distances. Wherever the absorption occurs, this equal but opposite heat flow at a lower temperature results in a positive entropy change that exceeds in magnitude the entropy loss of the cloud so that the entropy of the universe increases.

Discussion of Possible Objections

One may anticipate a few objections that some may offer to the thoughts presented here. One objection is to question the use of the virial theorem. There are two answers to this objection. First, many recent creationists believe that the sun derives at least part of its energy from gravitational contraction. The virial theorem is essential to this process and must be assumed to obtain the Kelvin-Helmholtz timescale of a few tens of millions of years as the maximum age of the sun. Denial of the validity of the virial theorem amounts to denial of the Kelvin-Helmholtz mechanism. Second, note that in the considerations here it was never assumed that the virial theorem is exactly true. All that was necessary was to assume that the virial theorem is only crudely correct, that is, that only some portion of energy liberated by gravitational contraction be radiated (or otherwise lost to the gas cloud, whether by radiation, magnetic affects, or other processes). If a portion of energy liberated is not shed, then all energy liberated must heat the gas, with no radiation losses. What mechanism could constrain this?

Another objection may be to point out that the model that Mulfinger used from the literature was surrounded by a much hotter gas than the contracting gas cloud itself. Even today this is a common scenario for collapse to form a star. Williams (2000) recently raised this issue and asked how a cooler object may radiate heat to a hotter one. The answer is that it does not. Instead, the material in the hotter outer cloud may be dispersed enough that it is transparent to infrared radiation, so that the radiation passes through the hotter gas to be absorbed in a more distant, cooler region. A similar process occurs on any calm, clear night. Objects near the ground emit infrared radiation that passes through the air above so that those objects cool to temperatures quite a bit below the temperature of the air. Williams' analysis would seem to prohibit this. Even in a dense interstellar cloud the gas is about fourteen orders of magnitude less dense than air at STP.

Williams went on to quote the thermodynamics expert Prigogine (1967) to the effect that entropy "absorption" in one part of system cannot be compensated by entropy "production" in another part of the system. No one is suggesting that the entropy decrease of the collapsing gas cloud is magically cancelled elsewhere in the universe. Every photon that is emitted results in an entropy decrease for the gas cloud, but each photon must be absorbed somewhere else, which results in an entropy increase. The two events are causally and thermodynamically related, so there is no appeal to connect two unrelated entropy changes, which is what I think that Prigogine is referring to. At any rate, Sommerfeld (1956) makes it clear that heat leaving an open system can reduce its entropy without violating the second law.

Conclusion

The calculations presented here show that contrary to common belief among recent creationists, the collapse of a pre-stellar cloud does not violate the second law of thermodynamics. Creationist speakers are urged to discontinue use of this argument. Does this mean that the process of stellar formation from clouds of gas is possible? There is still a seemingly insurmountable problem remaining (Cox and Giuli, 1967; Mulfinger, 1970; Novotny, 1973; Shklovskii, 1978). A large, tenuous cloud of gas and dust typically found in the interstellar medium simply lacks the gravitational attraction necessary to overcome the thermal motion of the gas. If a portion of the gas is contracted the temperature and pressure of the gas increases enough to expand the gas. Thus virtually all clouds are stable against collapse.

Only if the gas cloud is collapsed to a critical size (called the Jean's length) by some other mechanism can gravitational collapse work. Several mechanisms have been suggested, but each suffers from serious difficulties. One mechanism is the explosion of a nearby supernova to compress the gas sufficiently to start gravitational collapse. This obviously encounters the chicken and egg problem: how did the star that experienced the supernova form? Another suggested mechanism to initiate the collapse is a spiral density wave traveling around the galaxy. The spiral density wave may explain spiral structure of the galaxy and some other related phenomena from an evolutionary viewpoint, but its origin is not clear. One scenario for the origin of density waves is many nearly simultaneous supernovae explosions from the earliest generations of stars. Again the objection can be raised of how the first generations of stars were formed. Another popular starting mechanism for pre-stellar cloud collapse is cooling of the deep interiors of clouds by molecules and dust. Production of molecules in the interstellar medium can only be accomplished in an environment that contains dust, which can only be formed in the outer layers of red giant stars. Furthermore, with the exception of H_2, all interstellar molecules involve elements heavier than helium. According to the standard cosmology, elements heavier than helium are not primordial, and so must have been manufactured through nucleosynthesis in earlier generations of stars. Therefore both molecules and dust require that some stars must first exist.

All of the suggested mechanisms for initiating the collapse of a gas cloud into a star require the pre-existence of some stars. How the very first stars formed is probably the greatest problem for stellar evolution, and in recent years much theoretical work has addressed this. The issue of how a cloud is supposed to commence collapse down to the Jean's length is still a very fruitful pursuit for creationists, and a future detailed article devoted entirely to recent developments would be most desirable.

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Book Review

God's Equation by Amir D. Aczel
Dell Publishing, New York. 2000, 236 pages, $10.95

This is the latest book by the internationally known mathematician Amir Aczel whose best known book is *Fermat's Last Theorem* (1997). Aczel uses mathematics and its history to explain in layman's terms how the original solution of a specific mathematical problem was developed. The problem he addresses in this book is Einstein's attempt to explain all the known physical laws within the universe with one equation and therefore the title *God's Equation*. Aczel reveals that his concept of God is not the personal God of the Bible. He uses both the words create and evolve almost interchangeably, and believes in a Big Bang (p. xi) and the evolution of life (p. 10). Aczel believes there is a God who created the universe: "When the final equation is constructed, we should be able to use it to solve the wonderful riddle of creation. And perhaps that's why God sent us here in the first place" (p. 220).

The book subtitle is "Einstein, Relativity, and the Expanding Universe." It tells the story of how Einstein first developed his special theory of relativity (ch. 2), and then went on to the general theory of relativity (ch. 3) and his famous field equation of gravitation (chs. 4 and 8). In parallel and sometimes redundantly he brings in the history of the mathematics that Einstein used to take the next step (chs. 4, 5 and 7). He also brings in the history of the experiments that have been performed to verify Einstein's theories (chs. 6, 9, 10 and 12). Aczel begins with a preface which tells the background of why he started the project and how he did the research to write this book. He reports the latest evidence from astronomers which was presented at 1998 meeting of leading cosmologists and astronomers at Fermilab near Chicago. The conclusion reached at this conference (p. 11) is that the new data requires the reintroduction of a cosmological constant which even Einstein had denounced in his later years as his "greatest blunder." The evidence astronomers Saul Perlmutter, Neta Bahcall, Erick Guerra and others have discovered is that the universe is expanding and actually is doing so at an ever-increasing rate. This discovery requires a new force in nature that has not been detected and which counteracts gravity (p. 203). In the final chapter Aczel shows how the equation Einstein developed with the cosmological constant comes close but does not completely describe what astronomers see. Aczel believes Einstein hinted at one of the missing pieces in his book *Out of My Later Years* (1950) where he wrote about his theory applying to gravitational fields only but not to the total field in space (p. 219).

I would highly recommend this book to anyone interested in astronomy or cosmology. The book has footnotes, references and an index. The general reader should conclude from this book that mankind still does not understand how this universe came into existence or how it works even with all the evolutionists' proclamations to the contrary. The young earth creationist reader can be encouraged that there is strong evidence for the Creator. And He has revealed in His Word how and why this awesomely complex universe was created which mankind is still striving to understand.

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