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SOLAR MODELS OF LOW NEUTRINO-COUNTING RATE: THE CENTRAL BLACK HOLE

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ABSTRACT

Partial evolutionary sequences have been calculated for several solar models with central black holes of order $10^{-5}\ M_{\odot}$. If these are assumed to radiate their Eddington limiting luminosity, the central temperature is depressed to the extent that the predicted count rate for the ^{37}Cl solar neutrino experiment nears the current upper limit of 1 SNU; this occurs when the auxiliary energy source provides about half of the solar luminosity. Count rates below this limit would result from an even larger black-hole luminosity. Consequences for stellar evolution of the occasional presence of black holes inside normal stars are discussed.

Subject headings: black holes — interiors, solar — neutrinos

I. INTRODUCTION

The solar neutrino problem has now become serious. Standard solar models are predicting counting rates for the Brookhaven ^{37}Cl experiment of the order 5.6 SNU (Bahcall *et al.* 1973; Newman 1975), while the observed level is currently 0.2 ± 1.0 SNU (Davis and Evans 1973). Ulrich (1974) indicates that the discrepancy between the prediction of the standard models and the Davis experiment is now $2.7\ \sigma$, and he reviews the efforts to produce solar models whose neutrino flux is not in conflict with the observations by invoking special neutrino quenching mechanisms. None of these has been entirely successful. One mechanism has proven capable of producing a neutrino count rate below the 1 SNU limit while continuing to power the Sun by nuclear reactions (Clayton *et al.* 1975), but it is based on an ad hoc depletion of the high-energy tail of the Maxwell distribution which may turn out to be unphysical. Along with the other models in which nuclear reactions provide the bulk of the solar power, it shares the difficulties imposed by the *pep* limit ($\sim$0.3 SNU), which may already have been passed.

For these reasons we have been led to consider an alternative source of energy for the Sun, viz., a black hole accreting mass. In § II we discuss how such an object might have found itself inside our Sun. In § III we discuss how we treat the presence of a central black hole with a standard stellar evolution computer code through modification of the central boundary condition, and in § IV we present the results of such calculations. In § V we discuss the consequences of these ideas for stellar evolution.

II. PRIMEVAL BLACK HOLES

It is perhaps possible that a black hole of Galactic origin could collide with the Sun and be captured by it. Most discussions of black holes concentrate on those produced in the Galaxy, involving masses of order $1\ M_{\odot}$, and these are therefore excluded. Hawking (1971) has proposed the existence of microscopic black holes remaining from the big bang, and one could imagine a protostar forming about one of these. Indeed, the mechanism of star formation is so poorly understood (Talbot and Arnett 1973) that one could even postulate that the presence of a primordial black hole is required as a nucleus for star formation. We will not go that far, but will assume that star formation about black holes is common enough to justify imagining the Sun in that situation. A star forming about too massive a black hole would have been rapidly consumed, and would now be unobservable. Thus only stars with relatively small central black holes could have survived to the present time. Hawking (1974) has recently suggested that isolated black holes do not have an effective temperature of absolute zero, but rather should radiate as if their surface temperature were

$$T_{\rm BH} = (\hbar c^3/8\pi kG)m^{-1} \approx 6.2 \times 10^{-8}(m/M_{\odot})^{-1}\ {\rm K}\,,$$

where we designate the black hole mass by m. Then their luminosity would be $L = 4\pi R^2 \sigma T^4 \approx 9 \times 10^{-22}(m/M_{\odot})^{-2}$ ergs s^{-1}, where we have used for R the Schwarzschild radius $R_{\rm BH} \approx 3 \times 10^5\ m/M_{\odot}$ cm. This spontaneous luminosity is clearly not a significant rate for any macroscopic hole, but a microscopic black hole of mass less than about $10^{-19}\ M_{\odot}$ will have radiated away its rest mass energy in the roughly 3×10^{17} s available since the presumed big bang, as Hawking has pointed out. Thus we should apparently not consider seed masses smaller than $10^{-19}\ M_{\odot}$.

A black hole in a dense medium tends to accrete mass at the hydrodynamic rate (Novikov and Thorne 1973)

$$\dot{M} \approx 5(m/M_{\odot})^2(\rho/100\ {\rm g\ cm^{-3}})T_6^{-3/2}\ M_{\odot}\ {\rm s^{-1}}\,. \qquad (1)$$

Our model will propose that this is not the relevant accretion rate, however. An accreting black hole emits radiation by various processes, which, for the case of the small solar hole, we assume do not involve the production of observable neutrinos. We describe the rate of energy release by

$$L = f\dot{M}c^2\,, \tag{2}$$

where the efficiency factor f for the conversion of matter to energy is not well known, but has been estimated by others as perhaps about 0.1. We note that for nuclear reactions alone f is only about 0.01.

As the hole accretes, it grows as

$$\frac{dm}{dt} = (1 - f)\dot{M}\,, \tag{3}$$

where $\dot{M}$ is the rate at which mass is accreted. But as the mass increases, the rate of accretion, and therefore the luminosity, increases; eventually the luminosity approaches the Eddington limit, at which the luminosity pressure balances gravity. Numerically, its value is

$$L_E = \frac{0.13}{\kappa}\frac{m}{10^{-5}\,M_\odot}L_\odot\,, \tag{4}$$

where κ is the opacity in cgs units. We assume that subsequent accretion is limited by radiation pressure. If the Eddington luminosity is maintained thereafter, the accretion rate is given by equation (2) with $L = L_E$, and we have with reasonable accuracy

$$m = m_0 \exp{(t/\tau)}\,, \tag{5}$$

where

$$\tau = \kappa\frac{f}{1 - f}1.13 \times 10^9 \text{ years}\,. \tag{6}$$

We have not used the hydrodynamic accretion rate (1) since we assume that it applies for only a very short time initially. From equation (4) we see that to obtain a significant fraction of the solar power we will be interested in black hole masses near $10^{-5}\,M_\odot$ currently, and need not be concerned with the $10^{-19}\,M_\odot$ lower limit on primeval hole masses. Our assumption that the accretion rate can be regulated by the Eddington limit seems plausible; however, detailed studies of the physics of the accretion could eventually suggest otherwise.

III. BLACK-HOLE BOUNDARY CONDITIONS

It appears possible that the Sun formed about a primordial black hole of mass $10^{-19}\,M_\odot$ or larger, which has grown until it is now of order $10^{-5}\,M_\odot$ and provides an appreciable fraction of the solar luminosity. The Schwarzschild radius of such an object today would be a few centimeters, and for any large radius normally considered in solar models the influence of the black hole will be quite remote. Therefore the details of the vicinity of the black hole were ignored, and the effects of the hole were taken into account in the evolution code by replacing the usual central boundary condition

$$M(1) = R(1) = L(1) = 0 \tag{7}$$

by what we call our *black hole boundary conditions* (Newman 1975), which apply at the first zone boundary:

$$M(1) = 2m \tag{8}$$

$$= m + \tfrac{4}{3}\pi R^3(1)\rho(1)\,, \tag{9}$$

$$L(1) = 0.34\frac{m}{10^{-5}\,M_\odot}L_\odot\,, \tag{10}$$

where the choice (8) specifies that a buffer region containing an additional mass m exist between the Schwarzschild radius and the first zone boundary, and (9) gives the radius at the first zone boundary. The luminosity (10) at the first shell boundary is equation (4) with the electron-scattering opacity for pure hydrogen.

IV. EFFECT ON SOLAR MODELS

The possibility of a black hole residing in the Sun was discussed by Stothers and Ezer (1973), who considered only the structural effects due to its extreme mass concentration, and concluded that the structural effects alone made the solar-neutrino problem worse. Their calculation neglected the contributions of the black hole luminosity, consideration of which, they added as a note in proof, could lower the neutrino flux. This is indeed the case.

Note that the luminosity of a black hole which is currently producing only a fraction of the solar luminosity and growing on the time scale (6) has been quite negligible until rather recently (for no more than the last 10^9 years). The early evolution of a star with such a black hole will be but little different from that of our standard model (Newman 1975). Therefore, complete evolutionary calculations were not performed for such stars, but black holes of various mass were instead incorporated into the evolved standard model as it approached solar conditions. The computation was continued until the models relaxed to their new equilibrium evolutionary track.

The results of such calculations are shown in Figure 1 in relationship to the standard solar model ($X = 0.737$, $m = 0$) of Clayton *et al.* (1975). For a sufficiently small black hole mass the structural effects investigated by Stothers and Ezer dominate, as evidenced by the behavior of the central temperature in the model with $m = 0.5 \times 10^{-5}\,M_\odot$. But as the mass of the hole is increased, the effect of the auxiliary power source is to drive down the luminosity as well as the central temperature and density. The word *central* refers to the central mass zone, rather than the exact center. Thus for the $X = 0.737$ series at $m = 1.5 \times 10^{-5}\,M_\odot$ the luminosity has dropped to near $0.8\,L_\odot$, and the convective core due to the central concentration of the new energy source extends out to $0.09\,M_\odot$. The solar luminosity can be regained by increasing the initial helium abundance. To avoid recalculation of the early evolution, we merely subtracted an amount ΔX from the hydrogen mass fraction uniformly throughout the star, and added an

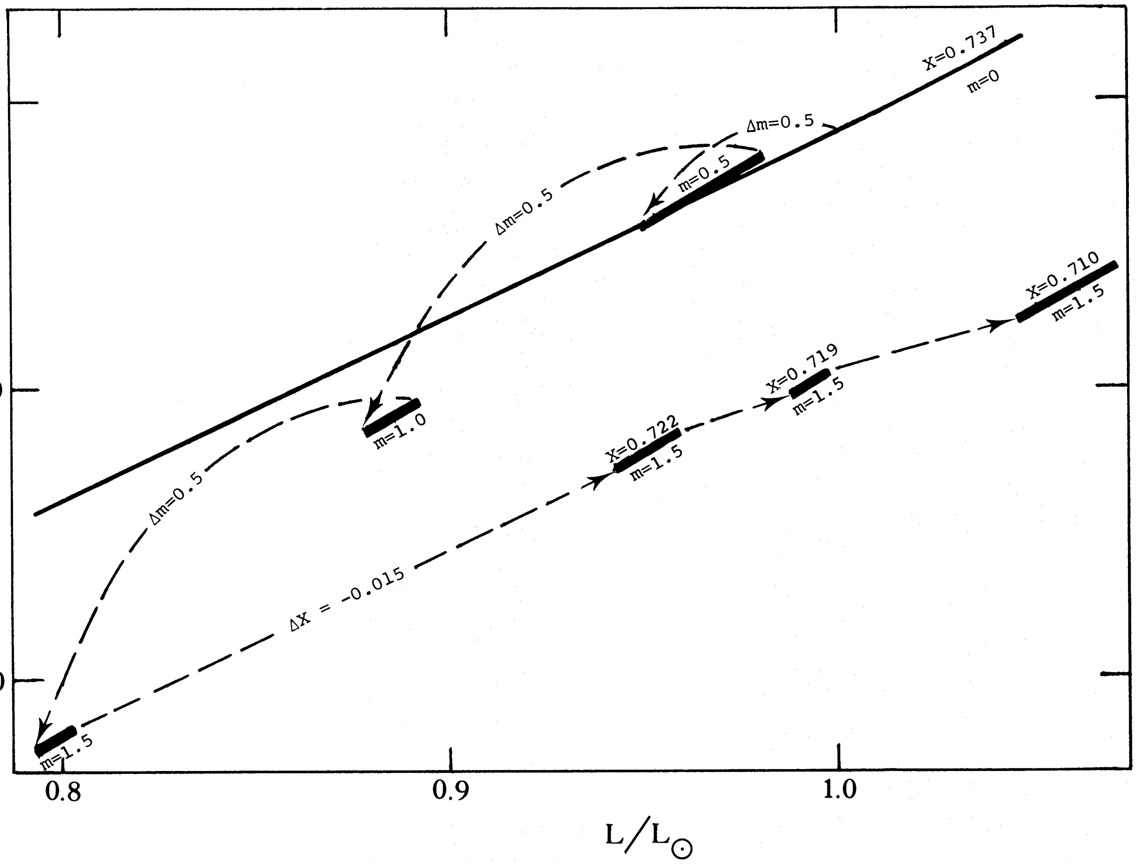

FIG. 1.—The central temperature and luminosity of the standard model of the evolving Sun are shown as the solid diagonal line. When the luminosity reaches $1.0 L_\odot$, a black hole having mass $m = 0.5$ (in units of $10^{-5} M_\odot$) is inserted. The dashed line shows the repositioning of the model owing to partial quenching of nuclear power at the slightly lower temperature. Subsequent evolution is shown as a short thick track. Further increases of m reposition the solar model by analogous dashed jumps, followed by short evolution tracks. The luminosity of the $m = 1.5 \times 10^{-5} M_\odot$ model is then restored from $0.8 L_\odot$ to $1.0 L_\odot$ by uniformly increasing the initial helium concentration.

TABLE 1

TWO SOLAR MODELS AT $L = L_\odot$

	$X = 0.737$, $m = 0$	$X = 0.719$, $m = 1.5 \times 10^{-5} M_\odot$
$T_c(10^6\ \mathrm{K})$	14.88	14.06
$\rho_c(\mathrm{g\ cm^{-3}})$	136.1	81.0
$M_{cc}/M_\odot$	0	0.08
$L_{BH}/L_\odot$	0	0.51
$\phi(pp)(\mathrm{cm^{-2}\ s^{-1}})$	6.13×10^{10}	3.05×10^{10}
$^*\phi(pep)(\mathrm{cm^{-2}\ s^{-1}})$	1.5×10^8	4.5×10^7
$\phi(^7\mathrm{Be})(\mathrm{cm^{-2}\ s^{-1}})$	3.55×10^9	1.23×10^9
$\phi(^8\mathrm{B})(\mathrm{cm^{-2}\ s^{-1}})$	3.03×10^6	4.56×10^5
$\phi(^{13}\mathrm{N})(\mathrm{cm^{-2}\ s^{-1}})$	2.65×10^8	4.34×10^6
$\phi(^{15}\mathrm{O})(\mathrm{cm^{-2}\ s^{-1}})$	1.81×10^8	3.36×10^6
SNU	5.6	1.0

* The *pep* flux was not calculated explicitly. It is assumed to scale as the product $\rho_c T_c^{-1/2} \phi(pp)$ from 0.26 SNU in the standard model.

NOTE.—M_{cc} is the mass of the convective core. L_{BH} is the luminosity of the black hole, whose neutrino emission is not included here.

equal amount to the helium fraction Y. In this way the integrated power $\int L dt$ is roughly conserved as we jump from one evolutionary track to another. In this approximation $L = L_\odot$ is restored at $X = 0.719$. A complete evolutionary calculation would doubtless require a slightly different initial composition, but certainly one within the limits of uncertainty in observed solar abundances.

The effect of these very low central temperatures on the neutrino fluxes is shown in Table 1, where the $X = 0.719$, $m = 1.5 \times 10^{-5} M_\odot$ model is compared with the standard model. The expected count rate is 1.0 SNU, and would be even lower if the hole luminosity exceeds the value $0.51 L_\odot$ that we ascribe to the black hole in Table 1.

Be reminded that the neutrino fluxes shown there are those from the bulk of the Sun and do not include any neutrinos that may be liberated due to accretion onto the black hole. A reliable estimate of these is difficult, but our preliminary studies indicate that the major source is the hot CN cycle operating in matter heated above 10^8 K near the black hole (roughly within $r = 10^5$ cm). The major neutrino sources would be from the decays of ^{14}O, which is not in the usual CN cycle, and of ^{15}O, which is. An upper limit to these fluxes is set by assuming that in the accreted matter, all of the hydrogen is fused to helium during the accretion. The rate of accretion needed to provide half the solar luminosity (as in the $m = 1.5 \times 10^{-5}\, M_\odot$ model) is $\dot{M} \approx 2 \times 10^{12}$ g s$^{-1}/f$. If we take this matter in today's Sun to be half helium before accretion, the associated upper limit to the neutrino fluxes due to accretion is

$$\phi_m(^{14}\mathrm{O}) = \phi_m(^{15}\mathrm{O}) \leq 0.5 \times 10^8 f^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,,$$

which corresponds to a counting rate of $0.04 f^{-1}$ SNU for each decay. Thus if the efficiency is 10 percent, the black hole accretion yields less than 0.8 SNU from these decays. Any thermal neutrino emission should be very small due to the small volume in which it can occur.

It is of considerable biological and geological interest that the past solar luminosity was greater than $1.0\, L_\odot$ in this model, unlike that of conventional solar models in which it was smaller in the past. The luminosity of our $m = 1.5 \times 10^{-5}\, M_\odot$ model would have been near $1.2\, L_\odot$ about 10^8 years ago (depending upon the size of τ), and has decreased since that time. Perhaps, therefore, planetary evidence can strengthen or refute this model.

V. CONSEQUENCES FOR STELLAR EVOLUTION

The difficulty is that the hole already contributes 51 percent of the luminosity at $m = 1.5 \times 10^{-5}\, M_\odot$. There is no fundamental reason that the black hole should not contribute nearly all of the solar luminosity, other than our prejudice in favor of nuclear reactions as the principal energy source (a prejudice that the solar neutrino experiment calls into question), but a large luminosity for the central black hole has consequences for the future of the Sun. The mass and luminosity of the black hole are growing exponentially on the time scale (6); and if the efficiency of the energy generating process is small, the Sun must soon (in a time short compared to 10^9 years) leave the main sequence.

This may or may not be in conflict with observational astronomy, depending on what fraction of stars contain black holes and the mass function for seed holes. If only very few stars form around black holes, the observational implications are slight on a statistical basis (very important for the few, however); but this makes the Sun a special case, an interpretation we would like to avoid (another prejudice, however). Note that if the seed black hole for a 1 $M_\odot$ star were much smaller than the Sun's seed, the hole would remain negligible throughout the star's main-sequence lifetime. During the late stages, luminosities are sufficiently high and time scales for nuclear fuel exhaustion are sufficiently short that the black hole will not be important then either, although it could perhaps play a role in the triggering of instabilities.

As another example, the H-R diagram of a globular cluster need show nothing noteworthy. It is so old that all stars except those containing at most very small black holes are now gone. There would be only a very small range of black hole masses that would seem to be relevant today in a globular cluster, and these few bizarre cases might not be recognized. It is in the young galactic clusters where one would more likely look for discrepant behavior. There the terminal stages of stellar life are a higher fraction of the age of the cluster, so terminal evolution is in that sense more visible. It is not clear what to expect, however. On our view the hole luminosity grows as the hole grows. The extent of the convective core becomes greater and greater as the hole luminosity increases. After the dip in luminosity when accretion first becomes important, the evolution would seem to be approximately up the main sequence until the accretion luminosity either disrupts the envelope or swallows it in a rather peculiar X-ray object. But while the star was moving up the main sequence, the fact that it would be undermassive would not necessarily be noticed, except perhaps in carefully studied clusters. The mass-luminosity relation would not apply well, and the surface gravity would seem to be too low for the stellar type. We cannot say more, and indeed this sketch may be wrong, for we have not yet pursued the evolutionary fate of such stars in a quantitative way. It does seem possible, however, that the existence of small central black holes within a fraction of the stars may not be in variance with the observational facts as they have been interpreted.

An objection to the suggestion can be raised if the efficiency of the matter conversion is too low (i.e., if f is too small), for the time scale (6) could become so short that we must be observing the Sun at a very special epoch in its evolution, in the twinkling when the luminosity of the black hole is of the same order as the hydrogen-burning solar luminosity. This would not be likely on the basis of *a priori* probability arguments, but it is presently hard to assess this argument.

In the spirit of imagining seed black holes for the formation of most stars, and noting that most stars seem to form in binary pairs, we might identify Jupiter as the missing companion of the Sun, and postulate that the activity of its tiny central black hole is responsible for that planet's high luminosity. The black hole mass required would be of order $10^{-13}\, M_\odot$.

VI. CONCLUSIONS

We have seen that the predicted count rate for the Brookhaven solar neutrino experiment can be reduced to near the currently observed upper limit by the presence of a central black hole which provides a large fraction of the solar luminosity by accretion of matter. It is possible to fit the presence of black holes inside a significant fraction of normal stars within the usual framework of stellar evolution while avoiding immediately obvious conflicts with observational astronomy. The time-scale requirements are, however, rather special, and there may be identifiable inconsistencies within the whole body of knowledge concerning stars.

It is difficult to decide subjectively how commonplace this phenomenon must be in order that it seem not unreasonable for the Sun. The suggestion offers, in any case, an alternative to nuclear energy sources for explaining the solar power output and perhaps for other astronomical phenomena as well. We therefore find the idea worthy of public scrutiny.

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