CIRCUMSTELLAR HABITABLE ZONES: ASTRONOMICAL CONSIDERATIONS

Daniel P. Whitmire
University of Southwestern Louisiana
Lafayette, LA 70504-4210

Ray T. Reynolds
Theoretical Studies
NASA Ames Research Center
Moffett Field, CA 94035

Abstract

From an astronomical perspective, stellar luminosity and its evolution in time are the dominant factors in determining the location, size and evolution of circumstellar habitable zones (HZ). Other stellar properties that can affect HZs are stellar temperature, mass, mass loss, spot coverage and multiplicity. Whether planets are likely to form within a star's HZ and under what conditions their orbits would be dynamically stable for significant periods of time are separate important questions. In this paper we review these topics and suggest areas for future work in light of the recent proposal (Goldin 1994) that NASA adopt as a new unifying focus the search for a habitable planet around a nearby star.

INTRODUCTION

Following Kasting, Whitmire and Reynolds (1993; hereafter KWR) and others, we define the habitable zone as the radial shell around a star within which an Earthlike planet could support surface liquid water. For our purposes an Earthlike planet is one similar in mass and composition to Earth and having comparable surface inventories of CO_2, H_2O, and N_2. The upper mass limit is

large enough for
Carbonate / Silicate
cycle to stabilize
the climate.

not well constrained but the lower mass must be sufficient to maintain adequate geological activity in order for the carbonate-silicate cycle to stabilize the climate. If we require stability for ≥ 1 Gyr then a mass greater than ~ 0.1 $M_\oplus$ is necessary based on the geological history of Mars (see below). We restrict our discussion to Earth-type habitats and terrestrial-type life, ignoring the possibility that life may have evolved in such marginal habitats as small planets (McKay and Davis 1991) or tidally heated environments (Reynolds et al. 1983, 1987).

KWR investigated climatic constraints on the inner and outer boundaries of the HZ. The inner boundary was assumed to be defined by the loss of water from the planet by either the moist or runaway greenhouse and the outer boundary by the freezing of all water on the planet's surface. Exactly when these circumstances occur was shown to be sensitive to the effects of H_2O and CO_2 clouds on the planet's radiation budget. Three different sets of flux limits—two theoretical and one observational—were identified for each boundary. The inner and outer boundaries of the HZ around mature main sequence stars depend primarily on stellar luminosity and to a lesser extent on temperature, both of which vary in time as a star evolves. Because of this evolution a planet will remain within the HZ only for a finite amount of time, τ, which is generally less than the main sequence lifetime of the star.

In the most elaborate previous modeling study of the extent and duration of HZs around stars, Hart (1978, 1979) defined τ to be 4.5 Gyr, and called the radial range within which an Earthlike planet could remain habitable for this length of time the continuously habitable zone (CHZ). We continue to use this terminology with the stipulation that τ is a parameter and that it need not necessarily begin at the zero age main sequence (ZAMS).

Hart (1978) concluded that the 4.5 Gyr CHZ for the Sun extended from 0.95 AU to 1.01 AU. This estimate was subsequently revised to 0.96 AU to 1.00 AU (Hart 1979). According to Hart, if the Earth had been closer than 0.96 AU to the Sun it would have experienced a runaway greenhouse within 4.5 Gyr, while if it had been farther from the Sun it would have undergone runaway glaciation. In his model, the Earth's habitable climate survived by sheer coincidence. The appearance of free oxygen and the resulting loss of an assumed reducing primordial atmosphere occurred before a runaway greenhouse developed, but after the danger of runaway glaciation had subsided. As discussed in KWR, the most important distinction between our model and Hart's is our assumption that the climate is stabilized by the carbonate-silicate cycle (Walker et al. 1981, Kasting 1988). This cycle provides a negative feedback by which the ambient amount of atmospheric CO_2 naturally regulates itself to maintain an average surface temperature above 273 K. In

our model the I
precise planeta
spheric events,
do not rule out
gases early in E
explain Earth's
contributes to
Watson 1982,
physical carbo
in the absence

Hart (1
with masses di
narrower for
altogether arou
spectral types
type stars in
assumption th
the same time
this stage in
increased mu
runaway glac
support argu
Galaxy is ne
Carter 1983,
climate mode
consequently,

Since
improvements
carbonate-sili
early Mars, K
outer bounda
orbit of Mars
condensation
greenhouse v
Whitmire et
calculations.
model to dire
outer HZ bou
evolutionary
range of stell

The n
Sun and othe
planets migh
around M sta
main conclus
search for ha

our model the Earth's stable, long-term climate is not an accident of precise planetary placement, or a result of the timing of atmospheric events, but is rather a consequence of stable equilibrium. We do not rule out the possible presence of some reduced greenhouse gases early in Earth's history, but we do not require them in order to explain Earth's long-term habitability. On Earth, today, life also contributes to the regulation of atmospheric CO_2 (Lovelock and Watson 1982, Schwartzman and Volk 1989). However, the geophysical carbonate-silicate cycle can keep a planet habitable even in the absence of life.

Hart (1979) also calculated the 4.5 Gyr CHZ around stars with masses different from the Sun and found that it was generally narrower for stars less massive than the Sun and disappeared altogether around stars less massive than 0.85 $M_\odot$, corresponding to spectral types later than K0, which includes the majority of solar-type stars in the Galaxy. The reason for this result was the assumption that the original greenhouse gases were lost at exactly the same time as on Earth, about 2 Gyr after the planet formed. At this stage in their evolution, the lower-mass stars have not yet increased much in luminosity, so their planets would undergo runaway glaciation. Hart's results were subsequently used to support arguments that the probability of complex life in the Galaxy is negligible (e.g., Pollard 1979, Rood and Trefil 1981, Carter 1983, Barrow and Tipler 1986). As discussed below, our climate model is not subject to this type of instability and, consequently, our conclusions are quite different.

Since the early work of Hart, there have been many improvements in climate modeling. Based on the operation of the carbonate-silicate cycle and the geological evidence of water on early Mars, Kasting et al. (1988) and Fogg (1992) suggested that the outer boundary of the Sun's 4.5 Gyr CHZ extended to at least the orbit of Mars. However, these studies neglected the effect of CO_2 condensation, which places a serious constraint on the amount of greenhouse warming available at low solar fluxes (Kasting 1991). Whitmire et al. (1991) incorporated this effect in preliminary HZ calculations. KWR (see also Kasting 1996) used a more complete model to directly examine the climatic constraints on the inner and outer HZ boundaries. Here we use those results, along with stellar evolutionary models, to calculate the evolution of the HZ for a range of stellar masses.

The next two sections describe our model calculations for the Sun and other single main sequence stars. We then consider where planets might form relative to HZs, synchronously rotating planets around M stars, and binary star HZs. In the final section we give our main conclusions and point out several areas for future work in the search for habitable planets around nearby stars.

EVOLUTION OF THE SUN'S HABITABLE ZONE

In the standard solar model, the Sun began its life on the zero age main sequence (ZAMS) with a luminosity of 0.71 $L_\odot$, and a photospheric temperature a few hundred degrees less than the present value. Compared with today, it is likely that the early Sun rotated much faster, had a stronger and more active magnetic field and solar wind, had a greater emission of X-ray and UV radiation, and had a larger fraction of its surface covered with spots.

End of Sun's Main Sequence Stage luminosity will go up to 2.2 $L_\odot$

By the end of core hydrogen burning in about 6.5 Gyr, the Sun's luminosity will have increased to 2.2 $L_\odot$. It will then soar to ~ 2300 $L_\odot$ over the next ~ 1 Gyr as the Sun ascends the first red giant branch (Sackmann et al. 1993). During this phase the Sun will lose a significant amount of mass (~ 0.275 $M_\odot$), most of it just prior to the helium flash that terminates the red giant phase. At maximum luminosity the solar radius will extend to ~ 0.78 AU, depending on the rate and amount of mass loss. The next phase (~ 0.1 Gyr duration) is the horizontal branch in which the Sun's luminosity is ~ 40 $L_\odot$. This is followed by the second red giant or AGB (asymptotic giant branch) phase, in which the luminosity peaks at ~ 5200 $L_\odot$, depending on mass loss. After the thermally pulsing AGB phase and the planetary nebula phase, the ultimate fate of the Sun is to become a cooling white dwarf of mass ~ 0.54 $M_\odot$. Mercury and Venus will have been engulfed by the Sun during the red giant phases. The Earth's fate is less certain. Although the surface of the Sun will extend to one AU during the second red giant phase, prior mass loss will have caused the planet orbits to expand, ultimately by a factor of two. Sackmann et al. (1993) find that the Earth will marginally survive; however, they do not discuss the tidal decay of Earth's orbit, which would tend to counter the expansion due to mass loss.

r_1 = inner boundary radius of HZ
r_2 = outer boundary
$L(t)$ = Solar Luminosity at time t
S_1 = appropriate solar flux for inner boundary
S_2 = appropriate solar flux for outer boundary

These phases in the Sun's luminosity evolution were illustrated in KWR and are reproduced here in Figure 1; they are based on the models of Iben (1967a, 1967b, 1974) and Iben and Renzini (1983). These models do not agree in detail with the more recent model of Sackmann et al. (1993), which includes post–main sequence mass loss, especially in the peak luminosity of the first red giant phase. However, our primary interest here is in the main sequence phase, for which there is reasonable agreement.

Given the luminosity and temperature as a function of time, the evolution of the HZ can be calculated for a specific choice of critical fluxes defining the inner and outer boundaries from

Radii of Habitable Zone

Today

$r_1 = \sqrt{\frac{1}{1.1}} = 0.95$ AU

$r_2 = \sqrt{\frac{1}{0.53}} = 1.37$ AU

$$r_1 = \sqrt{\frac{L(t)}{S_1(T)}}$$

FIG. 1. *Luminos*
scale is broken a
to the helium fla
horizontal branc
phase is not illu
are omitted.

where $r_1(r_2)$
solar lumino
evolutionary
flux, which i
radii will be
units and the
at Earth's orb

KWR
the HZ. In fl
limits are 1.1
planetary wa
respectively

E

an its life on the
of 0.71 $L_\odot$, and a
es less than the
y that the early
active magnetic
f X-ray and UV
ce covered with

bout 6.5 Gyr, the
ill then soar to ~
he first red giant
the Sun will lose
t just prior to the
e. At maximum
U, depending on
hase (~ 0.1 Gyr
n's luminosity is
AGB (asymptotic
ks at ~ 5200 $L_\odot$,
lsing AGB phase
of the Sun is to
ercury and Venus
ed giant phases.
rface of the Sun
phase, prior mass
, ultimately by a
t the Earth will
the tidal decay of
xpansion due to

evolution were
igure 1; they are
4) and Iben and
ail with the more
cludes post–main
nosity of the first
ere is in the main
ement.

function of time,
specific choice of
ies from

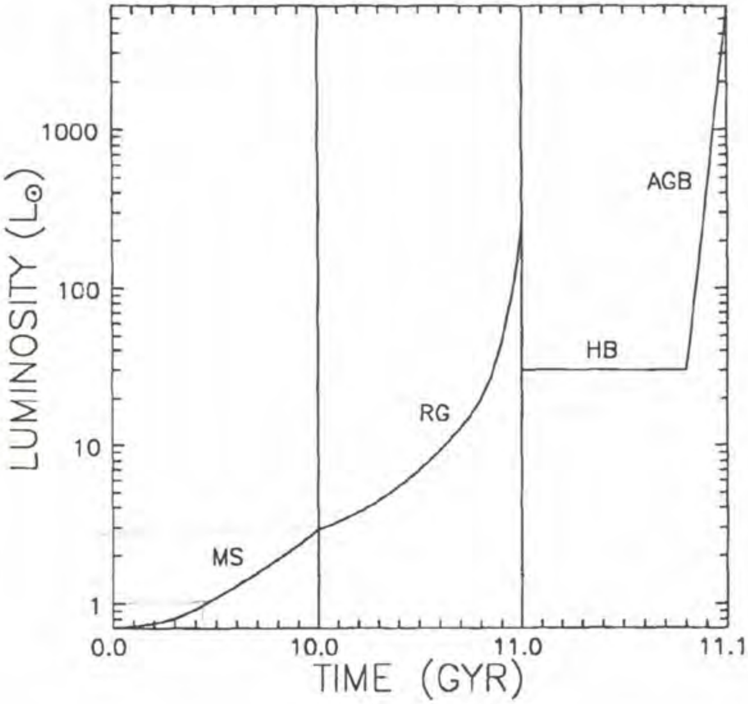


FIG. 1. *Luminosity evolution of a 1 $M_\odot$ star of solar composition. Note that the scale is broken at 10 and 11 Gyr. The discontinuity at 11 Gyr is real and is due to the helium flash. The phases are: MS = main sequence, RG = red giant, HB = horizontal branch, and AGB = asymptotic giant branch. The final white dwarf phase is not illustrated. Details of the evolution during the HB and AGB phases are omitted.*

$$r_2 = \sqrt{\frac{L(t)}{S_2(T)}}$$

where $r_1(r_2)$ is the inner (outer) HZ boundary radius, $L(t)$ is the solar luminosity as a function of time obtained from the stellar evolutionary model, and $S_1(S_2)$ is the appropriate critical solar flux, which in general is a function of stellar temperature. The HZ radii will be given in units of AU when the luminosity is in solar units and the flux is in units normalized to the present solar constant at Earth's orbit, which is taken to be 1360 W m^{-2}.

KWR identified three critical fluxes for the inner radius of the HZ. In ~~flux units~~ normalized to the present solar constant these limits are 1.1, 1.4, and 1.76. The first two result from the loss of planetary ~~water by the moist~~ greenhouse and runaway greenhouse, respectively (Kasting 1988). These are theoretical values obtained

Fluxes for inner radius
1.1 –
1.4
1.76

For Sol using

$S_1 = 1.1$

$S_2 = 0.53$

For Luminosity = 0.74

$r_1 = \sqrt{\frac{0.74}{1.1}} = 0.82$ AU

$r_2 = \sqrt{\frac{0.74}{0.53}} = 1.2$ AU

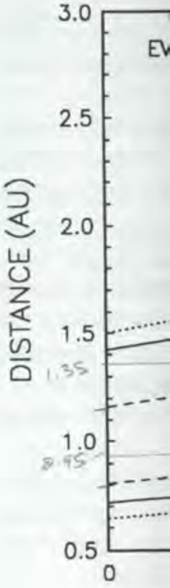
from a one-dimensional radiative-convective climate model in which the radiative effect of clouds is parameterized by use of a high surface albedo. This assumption is expected to result in conservative limits: a real planet can probably maintain liquid water at a higher solar flux than calculated. The third limit is empirical and corresponds to the flux at Venus 1 Gyr ago. Spacecraft observations show no evidence that liquid water has flowed on the surface of Venus for at least the last 1 Gyr (Solomon and Head 1991). This flux limit is an upper bound since Venus could not have had significant water since then. The inner HZ radius is thus reasonably well bracketed. The evolution of these inner HZ boundary radii for the Sun is shown in the bottom three curves of Figures 2 and 3.

Three critical fluxes corresponding to the outer radius of the HZ were also identified by KWR. In normalized units these flux limits are 0.32, 0.36, and 0.53. The smallest and least conservative limit corresponds to the flux at early Mars 3.8 Gyr ago in the standard solar model. This limit is based on observations and arguments (e.g., Pollack et al. 1987) that early Mars had a warm and wet climate and therefore must have been in the Sun's HZ. (Due to its low mass of 0.1 $M_{\oplus}$ Mars is not an Earthlike planet as we define it. An Earth-mass planet at the distance of Mars from the Sun might have maintained a stable climate for a much longer period, as did the Earth.) The intermediate theoretical flux limit of 0.36 corresponds to the maximum possible CO_2 greenhouse heating, which occurs for a CO_2 partial pressure of ~ 8 bars (KWR, Kasting 1991). At higher CO_2 partial pressures, the increase in planetary albedo outweighs the increase in greenhouse heating. Since the actual solar flux at Mars 3.8 Gyr ago was 0.32 in the standard model, there is a theoretical discrepancy between these two limits. This discrepancy is at present unresolved, but might be explained by the presence of other greenhouse gases in Mars' early atmosphere (Kasting 1991, Sagan and Chyba, abstract, this volume) or by a nonstandard solar model in which the Sun's ZAMS mass was somewhat greater than the present value (Graedel et al. 1991; Whitmire et al. 1995a,b; Doyle et al. 1995, 1996). In addition to this model, other possible astronomical explanations for an increase in the solar flux at early Mars (such as sunspot focusing) have been discussed by Whitmire et al. (1995a,b).

outer boundary!

$\boxed{0.53}$

The most conservative flux limit for the outer boundary is the "first condensation" limit of 0.53. This is the flux at which CO_2 first begins to condense and to increase the planetary albedo. This limit is probably too conservative, but is difficult to improve on without a climate model that can handle CO_2 clouds. These three estimates of the critical minimum flux necessary to sustain a mean



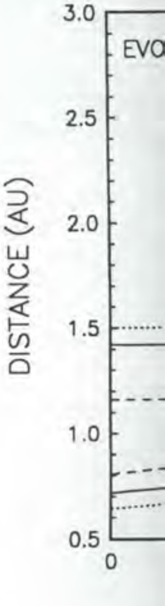


FIG. 3. *Evolution*
the outer HZ bo
value. The three c
dashes), the inter

limate model in
rized by use of a
cted to result in
maintain liquid
he third limit is
yr ago. Spacecraft
has flowed on the
lomon and Head
us could not have
Z radius is thus
these inner HZ
m three curves of

outer radius of the
d units these flux
least conservative
3 Gyr ago in the
observations and
Mars had a warm
in the Sun's HZ.
arthlike planet as
of Mars from the
or a much longer
oretical flux limit
CO_2 greenhouse
of ~ 8 bars (KWR,
s, the increase in
eenhouse heating.
was 0.32 in the
cy between these
ved, but might be
ases in Mars' early
abstract, this vol-
the Sun's ZAMS
lue (Graedel et al.
1996). In addition
planations for an
sunspot focusing)
.

outer boundary is
flux at which CO_2
etary albedo. This
ult to improve on
louds. These three
to sustain a mean

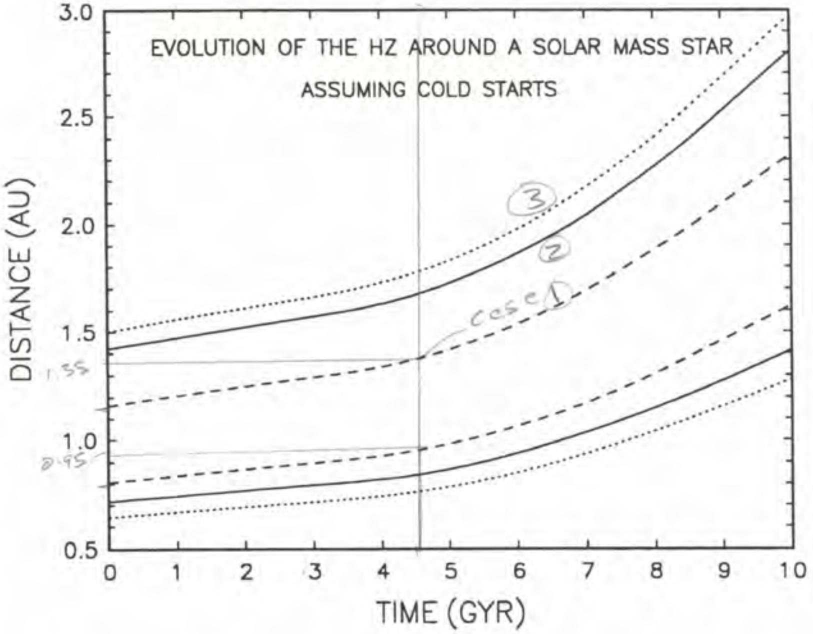


FIG. 2. *Evolution of the HZ around a 1 M$_\odot$ star assuming that an ice covered planet that was initially beyond the outer HZ boundary can be cold started. The three cases shown are discussed in the text and correspond to the most conservative Case 1 (long dashes), the intermediate Case 2 (solid curves), and the least conservative Case 3 (short dashes).*

most conservative
Case 1 1.1 0.5
1.1, 0.53

Case 2 1.4 0.3
1.4, 0.36
Case 3, 1.76 0.3
1.76, 0.32

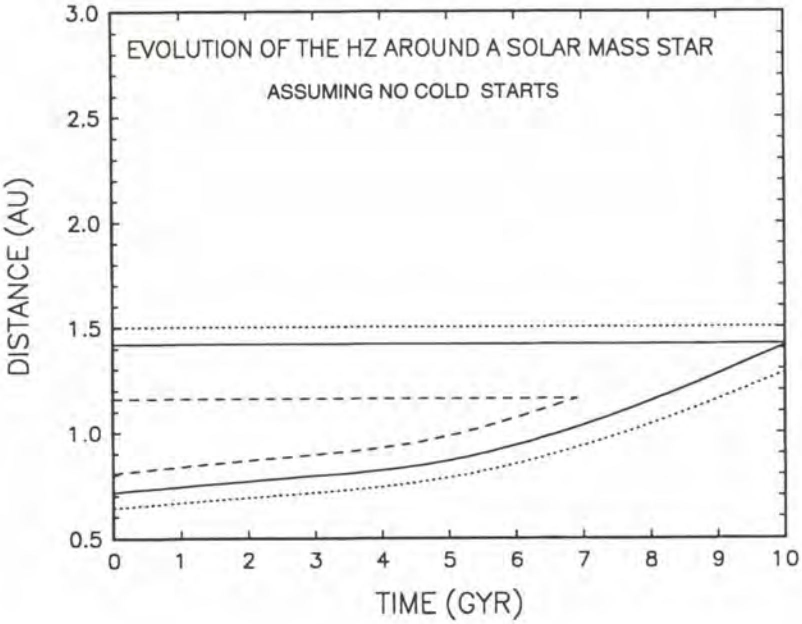


FIG. 3. *Evolution of the HZ around a 1 M$_\odot$ star assuming that an ice covered planet that was initially beyond the outer HZ boundary cannot be cold started until the stellar flux is greater than the critical greenhouse value. The three cases shown are discussed in the text and correspond to the most conservative Case 1 (long dashes), the intermediate Case 2 (solid curves), and the least conservative Case 3 (short dashes).*

surface temperature of 273 K were used, along with the 1 $M_\odot$ main sequence evolution model of Iben (1967a), to generate the evolution of the outer HZ boundary radii (three upper curves) in Figures 2 and 3.

These figures show the evolution of the Sun's HZ—the inner and outer radii versus time—for sets of the paired critical fluxes. The three sets are paired in the following way. Case number 1 corresponds to the two most conservative flux limits, the moist greenhouse (1.1) and the first condensation point (0.53). Case number 2 is the intermediate case and corresponds to limits determined by the runaway greenhouse (1.4) and the maximum greenhouse (0.36). Case number 3 is our least conservative case and corresponds to limits inferred from the lack of water on Venus as of 1 Gyr ago (1.76) and the evidence for the presence of liquid water on early Mars (0.32).

Problems with
Cold Starts

The time evolution of the three HZ cases shown in Figure 2 is based on the assumption that a planet that is initially beyond the outer boundary of the HZ and therefore frozen, will melt (deglaciate) once the solar flux reaches a value equal to our calculated climatic limits. As discussed by Caldeira and Kasting (1992), this assumption may not be valid. A planet that formed beyond the outer boundary of the HZ would develop a reflective blanket of ice. This ice layer might increase the planetary albedo, reducing the absorption of solar radiation. Such a planet would also be likely to develop thick, highly reflective, CO_2 clouds (Kasting 1991), further reducing the solar flux at the surface. A planet that undergoes global glaciation soon after accretion might remain in that state even when the solar flux increases beyond the appropriate (lower) critical value discussed above. Thus, it may be impossible to "cold start" an initially frozen planet before the solar flux increases by a factor of ~ 2 and is then greater than the critical greenhouse value (Caldeira and Kasting 1992). If cold starts are possible it can be seen from Figure 2 that the HZ moves outward and becomes broader in time.

Figure 3 shows the same evolution as Figure 2 but with the more conservative assumption that cold starts are not possible during the main sequence phase. In this case the outer boundary of the HZ is constant and equal to its ZAMS value. The inner boundary radius moves outward in time as before so the HZ now becomes narrower in time. For Cases 1 and 2 the HZ disappears altogether by the end of the main sequence. Because of the significant differences in the HZ and CHZ in Figures 2 and 3, the question of whether planetary cold starts are possible is an important one for future work. It might be possible, for example, that a major climatic perturbation from equilibrium such as a massive impact or extensive vulcanism, could "jump start" a frozen planet.

Conti
can be read o
most conserv
CHZ extends
Hart's (1979)
4.5 Gyr CHZ
larger than H
the next secti
case the 4.5 G
possible and
we will see t
Hart are even

Figur
entire lifetim
are possible.
duration of or
of the first re
the vicinity of
25 to 55 AU
Although it i
distances arou
categorically
short-lived, a

EVOLUTION
OTHER STA

The sa
with masses
more massive
their lifetime
evolution of c
type stars it i
planets to forr
1989). The ma
M/L. Since L
1967a), $\tau_{ms} \propto$
greater than 2
the other extre
$\leq 0.5 M_\odot$ have
evolution in 1
to their ZAMS
the Galaxy, s
that they cou
points in the n
these stars as

Continuously habitable zones for any assumed time period can be read off Figures 2 and 3 for the three limiting cases. For our most conservative Case 1 fluxes without cold starts, the 4.5 Gyr CHZ extends from 0.95 to 1.15 AU, which is a factor of 5 larger than Hart's (1979) CHZ for the Sun. For our least conservative Case 3 the 4.5 Gyr CHZ extends from 0.75 to 1.9 AU, or a factor of 30 times larger than Hart's CHZ. For simplicity of discussion here and in the next section we shall focus on the intermediate Case 2. For this case the 4.5 Gyr CHZ extends from 0.84 to 1.77 AU if cold starts are possible and from 0.84 to 1.43 AU if they are not. In the next section we will see that the discrepancy between our CHZs and those of Hart are even greater for stars of lower mass than the Sun.

Figure 4 shows the evolution of the Sun's HZ throughout its entire lifetime, assuming (necessarily) that planetary cold starts are possible. The post–main sequence phases have a cumulative duration of only about 1 Gyr, almost all of which is in the ascension of the first red giant branch. By the end of this time, the HZ is in the vicinity of 10 to 20 AU according to the model of Iben (Fig. 4), or 25 to 55 AU according to the model of Sackmann et al. (1993). Although it is doubtful that Earthlike planets could form at these distances around a 1 $M_\odot$ star, this figure points out that one cannot categorically rule out even red giant systems as possible, although short-lived, abodes for life.

EVOLUTION OF THE HABITABLE ZONE AROUND OTHER STARS

The same type of HZ calculations can be performed for stars with masses different from the Sun's. Main sequence stars much more massive than the Sun have large HZs on an absolute scale but their lifetimes are too short to be of interest as sites for the evolution of complex organisms (Huang 1960). For the massive O-type stars it is doubtful whether there is even sufficient time for planets to form during their ~ 10^6 yr stellar lifetimes (Bodenheimer 1989). The main sequence lifetime of a star, τ_{ms}, is proportional to M/L. Since $L \propto M^{4.75}$ over the mass range of most interest (Iben 1967a), $\tau_{ms} \propto M^{-3.75}$. Here we restrict ourselves to stellar lifetimes greater than 2 Gyr, which corresponds to masses less than 1.5 $M_\odot$. At the other extreme, the low-mass main sequence M stars with masses $\leq 0.5\,M_\odot$ have lifetimes longer than the age of the Universe. Their evolution in 10 Gyr is negligible, so their 4.5 Gyr CHZ is identical to their ZAMS HZ. Although these are the most numerous stars in the Galaxy, several objections have been raised against the idea that they could support life-bearing planets. We discuss these points in the next section and conclude that it is premature to reject these stars as viable candidates for having habitable planets.

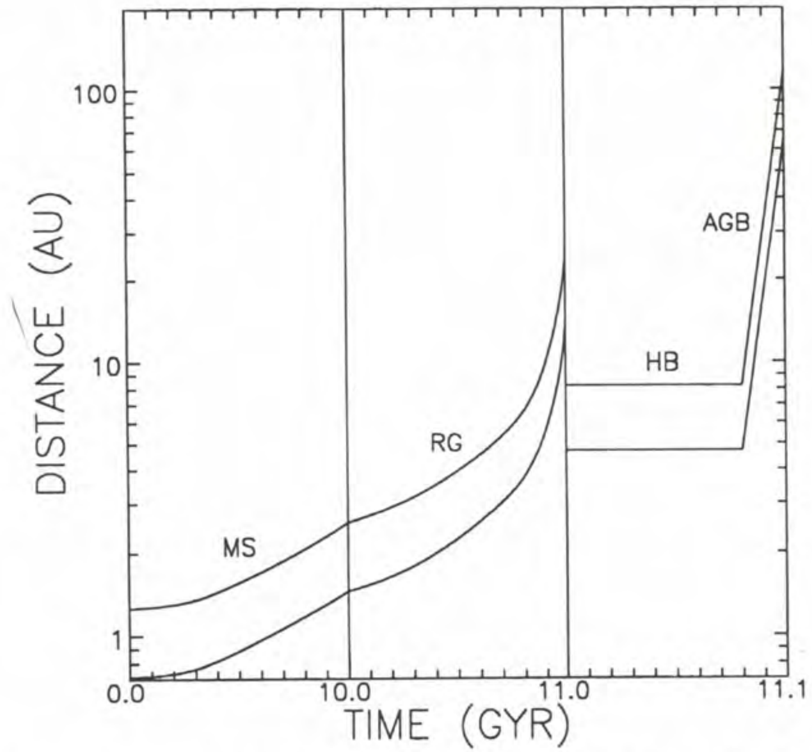
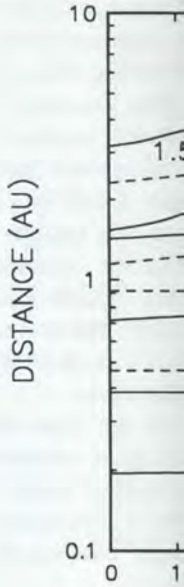


FIG. 4. *Evolution of the HZ during the entire lifetime of a 1 M$_\odot$ star. For the HZ to exist beyond 10 Gyr it is necessary to assume that cold starts are possible. Case 2 critical fluxes were used, and the phases shown are the same as those in Figure 1.*

Figures 5 and 6 show the evolution of the HZ (for Case 2 fluxes) around stars of selected masses between 0.5 and 1.5 $M_\odot$, with and without cold starts, respectively. The effect of stellar temperature on the wavelength distribution of light and, hence, on planetary albedo has been taken into account in all figures. The fluxes were corrected for stellar temperature by quadratically fitting and extrapolating the three stellar temperatures calculated in the climate model of KWR. Cases 1 and 3 would yield smaller and larger HZs, respectively, as illustrated in Figures 2 and 3. Stellar luminosities and temperatures were taken directly from Iben (1967a,b) for masses 1.25 and 1.5 $M_\odot$. Since Iben's 1 $M_\odot$ star does not precisely reproduce the present Sun's luminosity, we have normalized $L(t)$ to be consistent with this and with the solar model of Gough (1981). Iben does not give the complete evolution for 0.5 and 0.75 $M_\odot$ stars. For these cases we used his ZAMS luminosity, temperature and lifetime to generate our own model. This is an adequate approximation since these stars do not evolve much in 10 Gyr.



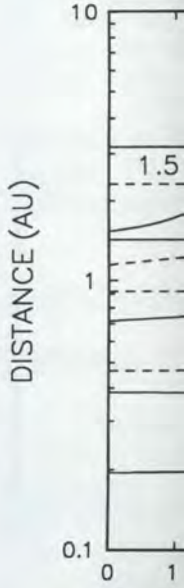
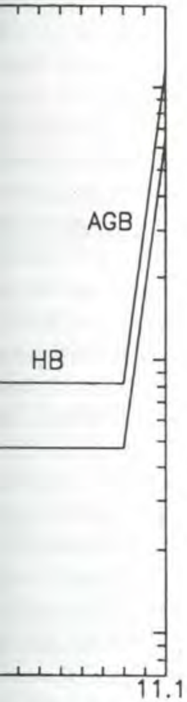


FIG. 6. *Evolution o*
starts are not poss
truncated at the end



$M_\odot$ star. For the HZ
ld starts are possible.
e the same as those in

he HZ (for Case 2
5 and 1.5 $M_\odot$, with
of stellar temper-
d, hence, on plan-
figures. The fluxes
atically fitting and
culated in the cli-
smaller and larger
nd 3. Stellar lumi-
rom Iben (1967a,b)
does not precisely
normalized $L(t)$ to
l of Gough (1981).
and 0.75 $M_\odot$ stars.
, temperature and
adequate approxi-
Gyr.

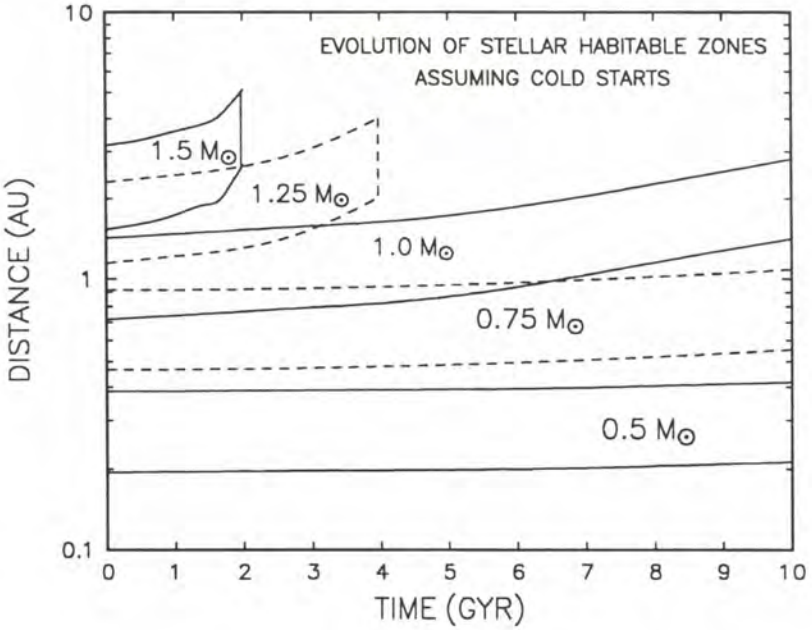


FIG. 5. *Evolution of the HZ around stars of different masses assuming that cold starts are possible. Case 2 critical fluxes were used and the evolution was truncated at the end of the main sequence phase.*

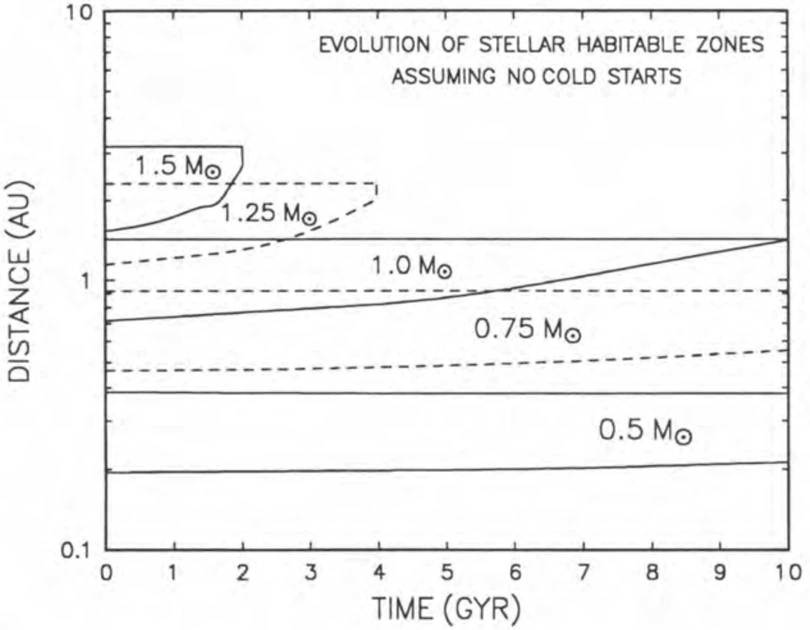


FIG. 6. *Evolution of the HZ around stars of different masses assuming that cold starts are not possible. Case 2 critical fluxes were used and the evolution was truncated at the end of the main sequence phase.*

For the stars in Figures 5 and 6, the widths of various CHZs can be read off for any assumed relevant time scale. Assuming no cold starts (Fig. 6), the CHZ for a given τ is equal to the HZ at time $t = \tau$. As in the case of the Sun, the 4.5 Gyr CHZs are much broader than those calculated by Hart (1979) for all stellar masses. Hart concluded that the 4.5 Gyr CHZ disappeared altogether for spectral types later than KO, corresponding to masses $\leq 0.85\ M_\odot$. Our results show that, even without cold starts, there is a significant 4.5 Gyr CHZ for all K and M stars. The CHZs for masses between 0.1 and 0.5 $M_\odot$ are essentially the same as the ZAMS HZ and can be obtained from Figure 7 or 8. As noted earlier, the main reason our model gives different results from Hart's is that it includes climate stabilization by the carbonate-silicate cycle.

The relevant CHZ time scale depends both on the type of life in which one is interested and on the rate of biological evolution. On Earth, intelligent life evolved in 4.5 Gyr, complex multicellular life in about 3.9 Gyr, and simple life within 1 Gyr after accretion. The extent to which these times depend on biological

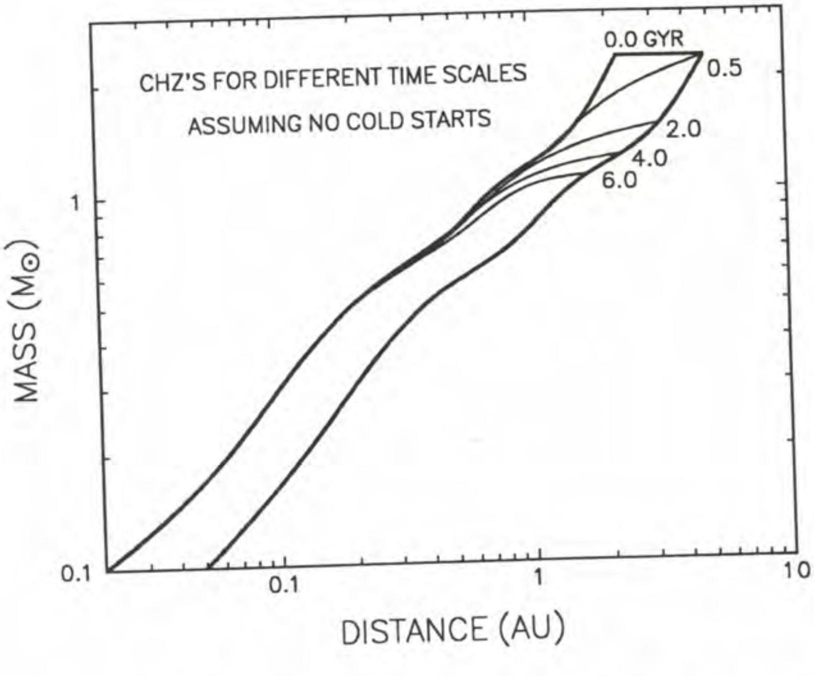


FIG. 7. *The CHZ for different assumed time scales, τ, for stellar masses in the range 0.1–2 $M_\odot$, assuming cold starts are not possible. The $\tau = 0$ outer envelope is the total HZ, from the inner radius at ZAMS to the outer radius at the end of the main sequence phase.*

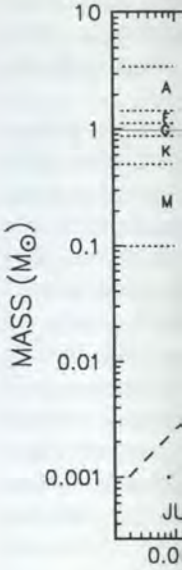


FIG. 8. *The ZAM
fluxes. The long
formation zone. T
in a circular orbit
damping. Note th
radius.*

evolution rates
question. One
CHZs for differ

DISCUSSION

Habitable Zo

In this
accrete relativ
simulations of
1996) resulted
masses ≥ 0.5 M
for a variety
suggested that
feature of solar
reached in ear
Wetherill's res
that there is a

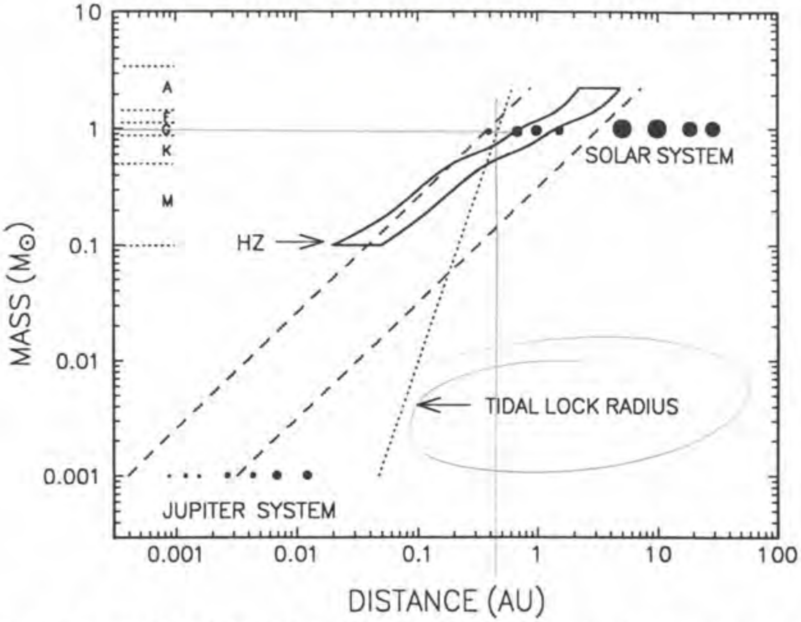


FIG. 8. *The ZAMS HZ (dark solid curve) as a function of stellar mass for Case 2 fluxes. The long-dash lines delineate the most probable terrestrial planet formation zone. The short-dash line is the radius for which an Earthlike planet in a circular orbit would be synchronously or slowly rotating as a result of tidal damping. Note that all such planets in the HZ around M stars are within this radius.*

evolution rates as opposed to planetary evolution rates is an open question. One way of covering the range of possibilities is to plot CHZs for different assumed time scales, τ (Fig. 7).

DISCUSSION

Habitable Zones and Planetary Accretion

In this section we consider where planets are most likely to accrete relative to the HZ. For the Solar System, numerical simulations of terrestrial planetesimal accretion (Wetherill 1991, 1996) resulted in an average of one to two terrestrial planets with masses ≥ 0.5 $M_\oplus$ forming per solar system between 0.6 and 1.4 AU, for a variety of initial conditions. On this basis, Wetherill suggested that the occurrence of Earthlike planets may be a common feature of solar-type planetary systems. A similar conclusion was reached in earlier simulations by Isaacman and Sagan (1977). Wetherill's results, together with our CHZ calculations, suggest that there is a high probability of at least one Earthlike planet forming in the (Case 2) 4.5 Gyr CHZ around solar mass stars. Even for our most conservative Case 1 evolution, the probability is ~ 0.5. Modeling of planetary accretion for stars of mass different from the Sun's is discussed by Wetherill (1996).

Evidence that protoplanetary nebulae are a common feature of low-mass star formation is found in observations of massive disks around young T Tauri stars and in observations of disks around many normal old main sequence stars, including G and later types (Aumann et al. 1984, Backman and Paresce 1993). A recent HST (Hubble Space Telescope) survey of over 100 young solar mass T Tauri stars in the Orion nebula found that fully half possessed observable protoplanetary disks (O'Dell and Wen 1994). Taking into account selection effects, it is estimated that at least half of all nearby main sequence stars have significant nonphotospheric IR excesses at IRAS wavelengths (10–100 μm). These excesses have been interpreted in terms of disks containing orbiting grains of sizes typically between one and 100 μm. In the case of β Pic the disk has been resolved optically (Smith and Terrile 1984). The lifetime of the observed grains due to various destruction mechanisms is generally less than the age of the star. Consequently, if the phenomenon is not transient, the observed grains must have larger sources, presumably planetesimals (Whitmire et al. 1988, Backman and Paresce 1993).

Extensive modeling of the IRAS data and observations at shorter and longer wavelengths have shown that the three prototype systems (α Lyr, α Psa, and β Pic) have gaps or holes in their inner disks of radii in the range ~ 20–80 AU. One possible explanation for the maintenance of these gaps against Poynting-Robertson and collisional diffusion is a planetary system. Roques et al. (1994) and Lazzaro et al. (1994) have recently investigated this possibility as an explanation for the gap and other disk structure in β Pic. Other explanations for the gap and the large-scale disk asymmetry are sublimation and a distant brown dwarf companion (Whitmire et al. 1988). To summarize, there is good evidence that, in general, protoplanetary nebulae are a common feature of star formation, but individual nebulae may differ significantly in various other properties such as mass, angular momentum, and magnetic structure, even around stars of similar mass.

We now wish to consider where terrestrial planets might form relative to the HZs of stars of different masses. The dark solid curve in Figure 8 shows the ZAMS HZ (for Case 2 fluxes) as a function of stellar mass. For stars with masses only slightly different from the Sun's, the zeroth order approximation is to assume Solar System planetary distances. Taking our own planetary system (which is typical of the Wetherill simulations) as an example, there would be two Earthlike planets, Venus and

---

Earth, within
Earth and Ma
may also have
However, onl
habitable for 4
fared better, i
around an ea
(Mercury) wou
F star would
sequence lifeti
only for τ ≤ 4.
(1991) simula
considerations
early K (mass
likely to have
this zeroth or
what higher a
planets.

For sta
1 $M_\odot$, we do
adequate. If it
in the Galaxy,
since the HZ
reality we exp
on stellar mass
mass stars. W
region might
other variable
being neglecte
region of plan
nature (Boden
might be expe
formation arou
(1989, 1995).

We co
sation in an op
perature is det
the distance at
primarily by th
temperature o
phase the lum
which is propo
a given compo
only approxim
radius and on
relatively smal

ar mass stars. Even
probability is ~ 0.5.
s different from the

e a common feature
ons of massive disks
f disks around many
G and later types
993). A recent HST
young solar mass T
ully half possessed
Wen 1994). Taking
that at least half of
nonphotospheric IR
These excesses have
biting grains of sizes
f β Pic the disk has
984). The lifetime of
tion mechanisms is
onsequently, if the
ins must have larger
et al. 1988, Backman

and observations at
own that the three
have gaps or holes in
80 AU. One possible
ps against Poynting-
ary system. Roques et
ntly investigated this
other disk structure in
the large-scale disk
wn dwarf companion
s good evidence that,
mmon feature of star
iffer significantly in
ular momentum, and
r mass.
restrial planets might
masses. The dark solid
or Case 2 fluxes) as a
masses only slightly
approximation is to
es. Taking our own
Wetherill simulations)
ke planets, Venus and

Earth, within the ZAMS HZ of an early K star and two planets, Earth and Mars, within the ZAMS HZ of a late F star. The Sun may also have had two planets in its ZAMS HZ, Venus and Earth. However, only for the early K star would both planets remain habitable for 4.5 Gyr. Thus, our own planetary system would have fared better, in terms of the a priori evolution of complex life, around an early K-type star. For middle (late) K stars, Venus (Mercury) would remain in the habitable zone for 4.5 Gyr. The late F star would have one planet, Mars, within its HZ for the main sequence lifetime. Stars more massive than 1.25 $M_\odot$ are relevant only for $\tau \leq 4.5$ Gyr. Similar results follow if we use the Wetherill (1991) simulations, rather than the actual Solar System. These considerations suggest that stars of spectral type between late F and early K (masses between approximately 1.25 and 0.85 $M_\odot$) are likely to have one or two planets within the $\tau \geq 4.5$ Gyr CHZ. In this zeroth order approximation the early K stars have a somewhat higher a priori probability of possessing long-term habitable planets.

For stars with masses that are significantly different from 1 $M_\odot$, we do not expect the zeroth order approximation to be adequate. If it were, it would predict that the most numerous stars in the Galaxy, the M stars, would not have any habitable planets, since the HZ would lie well inside the planet formation zone. In reality we expect that the planetary formation zone should depend on stellar mass and therefore that planets will form closer to lower-mass stars. We wish to approximate how the planetary formation region might scale with stellar mass in a statistical sense (i.e., other variables such as angular momentum and magnetic fields being neglected). Since the primary influence of a central star on the region of planet formation is directly or indirectly gravitational in nature (Bodenheimer 1989), an approximate mass scaling law might be expected. The more complex general problem of planet formation around stars of different masses is discussed by Lissauer (1989, 1995).

We consider first pre–main sequence (PMS) grain condensation in an optically thin nebula. In this case the local grain temperature is determined solely by the stellar flux. We assume that the distance at which various compounds condense is determined primarily by the local temperature. The distance at which a given temperature occurs, r, is proportional to $\sqrt{L_{PMS}}$. During the PMS phase the luminosity is the result of gravitational contraction, which is proportional to M^2. Thus, the distance at which grains of a given composition condense is proportional to M. This result is only approximate since L_{PMS} also depends on the contracting star's radius and on the contraction time scale. However, these effects are relatively small and they act in opposite senses. If the nebula is optically thick, the situation is more complicated: the local temperature then depends on the turbulent heat transfer properties of the disk in addition to the gravitational contraction energy. The trend should be the same, however, and the distance at which a given temperature is reached should still be proportional to mass. Using different physical arguments, Cameron (1963) has also suggested that planetary accretion distances scale with stellar mass.

We assume conservatively that, during the planet formation phase, the refractory silicate condensation radius, $a_1(M)$, for a 1 $M_\odot$ star lies inward of Mercury's orbit (0.39 AU) and that the condensation radius, $a_2(M)$, for water lies beyond the outer asteroid belt (3.2 AU). With these assumptions, we can generate two functions that should bound the most likely region for terrestrial planet formation by simply scaling linearly with stellar mass from these two Solar System values ($a_{1,2} \propto M$). These functions are plotted in Figure 8 as the two parallel dashed lines. Of course, as yet we do not know that terrestrial planets actually exist around other stars, but if they do, the dashed lines in Figure 8 should approximately bracket their accretion radii.

Our suggestion that planetary formation distances scale with stellar mass is consistent with two available examples—the Sun and Jupiter. The Galilean satellites may have formed from an optically thin Jovian nebula, analogous to the solar nebula (Pollack and Reynolds 1974). Jupiter's early luminosity would have then determined the temperature structure and thus the condensation region in the satellite nebula. Jupiter's innermost Galilean satellite, Io, is composed largely of rocky materials. The two large outer moons, Ganymede and Callisto, are H_2O rich. Europa has a significant amount of H_2O and represents the approximate transition region between rocky and icy bodies. Interestingly, it can be seen in Figure 8 that the lower dashed line, which represents the outer terrestrial planet formation boundary, passes through the Jupiter system near Europa, with Io (and several other smaller rocky satellites) lying well inside the zone. The Galilean moons, especially Io and Europa, may have undergone some orbital expansion since their formation, so their original orbits could have been somewhat farther inside the nominal terrestrial planet formation zone.

Except for the gap in the asteroid belt, the planets in the Solar System and the major satellites in the Jovian system are distributed approximately logarithmically with distance and are therefore spaced uniformly on a log scale as illustrated in Figure 8. The explanation for this spacing is at present unknown; it may simply represent a general tendency of accretion from a disk, or it may be coincidental. Assuming that the Solar System is not atypi-

---

cal we take the
a constant C,

We ass
Figure 8, that C
precise value of
purpose of com
the inner and o
number of plane

N_{HZ}

(For ma
interior to the t
integration limi
Mercury is prob
the argument of
discussion.) Th
Figures 5 and 6
M at time t, mu
plotted have th
number of plane

For the c
also corresponds
for τ = 4.5 Gyr
Consequently,
planets in their 4
stars have nearl
stars' log CHZ c
therefore, K sta
for having long-
if our assumpti
valid. If M stars
permanent glac
discussed in the
habitable plane
absolute size) H

Can Habitabl

The tidal
its HZ will be m
The inner HZ aro

nplicated: the local
at transfer properties
ntraction energy. The
distance at which a
proportional to mass.
ron (1963) has also
es scale with stellar

ng the planet forma-
n radius, $a_1(M)$, for a
39 AU) and that the
nd the outer asteroid
e can generate two
region for terrestrial
ith stellar mass from
These functions are
d lines. Of course, as
actually exist around
s in Figure 8 should

ation distances scale
ilable examples—the
have formed from an
solar nebula (Pollack
ity would have then
hus the condensation
innermost Galilean
terials. The two large
O rich. Europa has a
he approximate tran-
nterestingly, it can be
which represents the
, passes through the
several other smaller
The Galilean moons,
ergone some orbital
nal orbits could have
terrestrial planet for-

elt, the planets in the
he Jovian system are
with distance and are
llustrated in Figure 8.
ent unknown; it may
tion from a disk, or it
r System is not atypi-

---

cal we take the number of planets, dN, in the interval $d(\log r)$ to be a constant C,

$$\frac{dN}{d(\log r)} = C \qquad a_1(M) < r < a_2(M)$$

We assume, based on the mass scaling extrapolation in Figure 8, that C does not depend strongly on stellar mass. The precise value of C (~ 4 for the Solar System) is not important for the purpose of comparing different mass stars. Integrating dN between the inner and outer HZ boundaries, $r_1(M,t)$ and $r_2(M,t)$, gives the number of planets in the HZ at time t:

$$N_{HZ}(M,t) = C \int_{r_1}^{r_2} d(\log r) = C \log \left[\frac{r_2(M,t)}{r_1(M,t)} \right]$$

(For masses $\leq 0.3\ M_\odot$ a nontrivial part of the HZ lies interior to the terrestrial planet formation zone and so the lower integration limit should be a_1. Since our scaling of a_1 to the orbit of Mercury is probably too conservative and since this limit appears in the argument of a logarithm, we neglect this effect in the following discussion.) This result for $N_{HZ}(M,t)$ is readily interpretable in Figures 5 and 6 as the logarithmic width of the HZ of a star of mass M at time t, multiplied by a constant. At $t = 0$ all spectral types plotted have the same ratio, $r_2/r_1(\approx 2)$ and therefore the same number of planets in their HZs (~ 1).

For the case of no cold starts (Fig. 6), the HZ at a given time also corresponds to the CHZ for $\tau = t$. By inspection, the log CHZ for $\tau = 4.5$ Gyr is approximately the same for G, K, and M stars. Consequently, these stars should have comparable numbers of planets in their 4.5 Gyr CHZ. However, for $\tau \geq 4.5$ Gyr the K and M stars have nearly the same number of qualifying planets but the G stars' log CHZ diminishes, becoming zero at $\tau = 10$ Gyr. Overall, therefore, K stars and the abundant M stars are better candidates for having long-term habitable planets than are more massive stars if our assumptions of mass scaling and logarithmic spacing are valid. If M stars cannot be disqualified for other reasons (such as permanent glaciation due to synchronized planetary spins, as discussed in the next section) then they may possess most of the habitable planets in the Galaxy, notwithstanding their small (in absolute size) HZs.

Can Habitable Planets Exist Around M Stars?

Tidal Brakg

The tidal interaction between an M star and any planets in its HZ will be much greater than that between the Earth and Sun. The inner HZ around a $0.1\ M_\odot$ star is at a distance of only 0.04 AU, or about 15 stellar radii. At this distance the orbital period is nine days. Since a mature M star is expected to rotate with a longer period, this corresponds to a tidally unstable configuration (Counselman 1973). However, using the analysis of Lecar et al. (1976) and Zahn (1977) we find that the time scale for a 1 $M_\oplus$ planet in the HZ to spiral into a fully convective star is greater than a Hubble time scale.

It was pointed out by Dole (1964) that planets around M stars might be synchronously rotating as a result of tidal damping. The dotted line in Figure 8 is our calculated tidal radius, r_T. It is the distance at which an Earthlike planet in a circular orbit would become tidally locked in a specified amount of time, t, taken here to be 4.5 Gyr. The tidal radius in cgs units is given by Peale (1977) as

$$r_T = 0.027\left(\frac{P_0 t}{Q}\right)^{1/6} M^{1/3}$$

where P_0 is the original rotation period of the planet, Q^{-1} is the solid body plus ocean specific dissipation function, and M is the stellar mass. Today the Earth's Q is dominated by shallow seas and is ≈ 13. However, a value this small is inconsistent with the Earth-Moon system evolution, and the average solid body Q is presumably closer to 100 (Burns 1986). In calculating r_T in Figure 8 we used $Q = 100$, $t = 4.5$ Gyr, and $P_0 = 13.5$ h. Fortunately, r_T is relatively insensitive to the uncertainties in these parameters. Figure 8 shows that, after 4.5 Gyr of evolution, Earthlike planets in circular orbits lying within the HZ of stars of mass $\lesssim 0.5\ M_\odot$ will be synchronously rotating. This could result in the permanent freezing of all water and other volatiles on the dark hemisphere. Such freezing would certainly occur for synchronous rotation if the initial atmospheric pressure were sufficiently low. However, using a simple energy balance model, Haberle et al. (1996) find that only a modest surface pressure of ~ 100 mb, depending on stellar flux, is required to prevent the atmosphere from freezing out.

Burns

Things that might prevent synchronous orbits
- orbital resonances with other planets
- Atmospheric tides

These results suggest that synchronously rotating planets may be habitable. However, M star planets may not all be synchronously rotating in any case. There are at least two alternative possibilities in the Solar System. One is that planets might be prevented from achieving synchronous rotation. The existence of orbital resonances, such as Mercury's 3 : 2 resonance with Venus, would tend to prevent synchronous rotation from occurring. A different example of nonsynchronous rotation is illustrated by Venus. The small amount of retrograde rotation of that planet should damp out in a small fraction of 1 Gyr. It is suspected that atmospheric tides have stabilized the rotation rate and prevented syn-

---

chronous rotati
we note that, sy
be subjected to
would be a crit

Planets and

More th
binary or multip
systems have
habitable plan
instability of p
orbital stability,
distances (Lissa
The for
(1981) and Penc
circular, planet
was typically a
aration (externa
tem), or vice ve
more greater th
case—planet or
compared the
and McKenzie
analytical stud
criterion for ex
1986, Rabl and
therein) found
ratio, they obta
with observation
calculations for
for a relatively s
of other studies
see Hale (1994,
Using th
and Mayor (199
HZ results, we e
of external bina
short-term stabl
tested for stabilit
With reg
that an accretion
(Artymowicz et
mation is likely
dence that planet

bital period is nine
tate with a longer
nfiguration (Coun-
car et al. (1976) and
$M_\oplus$ planet in the
ater than a Hubble

planets around M
lt of tidal damping.
idal radius, r_T. It is
circular orbit would
ime, t, taken here to
by Peale (1977) as

e planet, Q^{-1} is the
nction, and M is the
ted by shallow seas
nconsistent with the
age solid body Q is
ulating r_T in Figure 8
h. Fortunately, r_T is
n these parameters.
, Earthlike planets in
nass ≤ 0.5 $M_\odot$ will be
e permanent freezing
k hemisphere. Such
s rotation if the initial
. However, using a
1996) find that only a
ling on stellar flux, is
ing out.
usly rotating planets
may not all be syn-
least two alternative
hat planets might be
tion. The existence of
esonance with Venus,
from occurring. A dif-
s illustrated by Venus.
of that planet should
suspected that atmo-
e and prevented syn-

chronous rotation from being achieved (Dobrovolskis 1980). Finally we note that, synchronized or not, planets around many M stars will be subjected to intensive flares, though it is not obvious that this would be a critical problem for habitability.

Planets and Habitable Zones in Multiple Star Systems

More than 65% of nearby solar-type stars are members of binary or multiple star systems (Duquennoy and Mayor 1991). These systems have sometimes been rejected as likely locations for habitable planets for two reasons—the suspected dynamical instability of planetary orbits, and the belief that, even granted orbital stability, planets would be unlikely to form at the required distances (Lissauer 1989).

The former objection was addressed by Graziani and Black (1981) and Pendleton and Black (1983), who found that stable, near-circular, planetary orbits existed when the planet's orbital radius was typically a factor of 5 or more larger than the binary separation (external case—planet orbits barycenter of the binary system), or vice versa, when the binary separation is a factor of 5 or more greater than the planet's distance from either star (internal case—planet orbits one star). More recently, Kubala et al. (1993) compared the Hill and Laplace stability criteria (e.g., Szebehely and McKenzie 1981) for the case of external planetary orbits. This analytical study supported the original Graziani-Black stability criterion for external orbits. However, other work (e.g., Dvorak 1986, Rabl and Dvorak 1988, Dvorak et al. 1989 and references therein) found a less restrictive limit. Rather than a factor-of-5 ratio, they obtained a factor-of-2 ratio, a result possibly at odds with observations of triple star systems. In these studies, numerical calculations for both internal and external orbits follow the systems for a relatively small number of stellar orbits (~ 500). For a review of other studies of the stability of planets in multiple star systems see Hale (1994, 1996).

Using the binary semimajor axes statistics of Duquennoy and Mayor (1991) and the Graziani-Black stability criteria and our HZ results, we estimate that ~ 50% of internal binaries and ~ 10% of external binaries could support habitable planets in at least short-term stable orbits. Numerical experiments have not as yet tested for stability on longer, more interesting, time scales.

With regard to the second objection it is generally expected that an accretion disk(s) will remain after binary star formation (Artymowicz et al. 1991). The time scale for planetesimal formation is likely to be short compared with the disk lifetime. Evidence that planetesimal accretion can occur is suggested by the fact that multiple star systems exhibit IR excesses with about the same frequency as do single stars (Backman and Paresce 1993). As discussed earlier in connection with single stars, these observations imply the presence of larger sources (planetesimals), indicating that accretion of planets is not necessarily ruled out dynamically.

According to Wetherill (1991) a perturbation capable of causing a relative velocity between planetesimals of 100 km/s would shut down runaway accretion and prevent embryo (Moon- to Mercury-sized bodies) formation. We have done preliminary numerical calculations that show this level of perturbation is readily achieved within the 10^4–10^5 yr time scale of runaway accretion in all but the widest (internal) binary systems. The typical solar-type binary has a separation of ≈ 38 AU and an eccentricity of ≈ 0.7 (Duquennoy and Mayor 1991). Assuming both stars formed at roughly the same time, this typical system and those with smaller semimajor axes may not accrete planets at and beyond one AU from the primary star. More separated systems will tend to have random eccentricities (mean = 0.7) and random relative inclinations (mean = 32 deg) between the expected planetesimal plane (= equatorial plane of primary star) and the binary orbital plane (Hale 1994). We find that many of these systems will produce the critical stirring velocity at one AU and that if a similar runaway accretion criterion is used at 5 AU only a small fraction of known binaries would accrete a Jovian planet. Jovian planets may be necessary to bring water and other volatiles and organics to terrestrial planets (Delsemme 1991) and/or shield habitable planets from excessive impacts (Wetherill 1994). It remains to be investigated under what conditions dynamical friction, collisions, or gas drag can relax relative velocities faster than a binary companion can accelerate them. In cases where a Jovian planet does not form but a terrestrial planet at one AU does, it is possible that under some range of parameters the companion star can simulate Jupiter's role in perturbing volatiles into the terrestrial region.

CONCLUSIONS AND FUTURE WORK

Recently it has been proposed (Goldin 1994) that NASA adopt as a "new unifying mission" the search for a habitable planet around a nearby star. In addition to observations, such a mission would require (1) knowledge of the location and extent of habitable zones around specific nearby single and multiple star systems, (2) an assessment of the formation and long-term stability of planetary orbits in the HZs of these systems, and (3) an evaluation of the habitability of synchronously rotating planets around M dwarfs, which are the most numerous of the nearby stars.

In this
these objective
employed a m
stellar evolutio
around stars o
and CHZs are
earlier model
may be indepe
conjunction w
ability of sync
M stars should
able planet. Fu
evolution of
models—for e
determining w
can subseque
increases.

Many
addressed in
nature. As dis
may shut dow
bation in a sin
vent the accr
somewhat mor
Assuming that
will then be po
planetary orbi
influence of th
be eliminated
for the numero
are typically tw
since any Jupit
closer to the
discovery of
calculations cou
modeled plane
binary star sys
planetary syst
sufficiently sta
candidates in t
body calculatio
planet was im
would likely
habitable plan
habitable plane
needed.

ith about the same
esce 1993). As dis-
these observations
simals), indicating
out dynamically.
rbation capable of
mals of 100 km/s
t embryo (Moon- to
done preliminary
of perturbation is
scale of runaway
nary systems. The
f ≈ 38 AU and an
91). Assuming both
typical system and
crete planets at and
parated systems will
≈ 0.7) and random
veen the expected
mary star) and the
hat many of these
city at one AU and
used at 5 AU only a
ete a Jovian planet.
and other volatiles
1991) and/or shield
Wetherill 1994). It
nditions dynamical
ive velocities faster
n. In cases where a
net at one AU does,
eters the companion
olatiles into the ter-

n 1994) that NASA
or a habitable planet
ions, such a mission
d extent of habitable
le star systems, (2) an
tability of planetary
an evaluation of the
s around M dwarfs,
rs.

In this paper we have focused primarily on the first of these objectives and reviewed results of recent HZ calculations that employed a modern climate model in conjunction with standard stellar evolution models to calculate the size and evolution of HZs around stars of various masses. Our main conclusions are that HZs and CHZs are an order of magnitude larger than suggested by an earlier model and that the average number of planets in the HZ may be independent of stellar type. This latter result, especially in conjunction with the results of Haberle et al. (1996) on the habitability of synchronously rotating planets, suggests that the nearby M stars should be considered candidates in the search for a habitable planet. Further progress in our knowledge of the location and evolution of HZs depends mainly on improvements in climate models—for example, by taking clouds into account directly and determining whether planets initially beyond the outer HZ radius can subsequently be "cold started" as the stellar luminosity increases.

Many of the astronomical problems that need to be addressed in the search for a habitable planet are dynamical in nature. As discussed in the previous section, a binary companion may shut down the runaway accretion process. A similar perturbation in a single star system by a Jupiter-mass planet might prevent the accretion of a terrestrial planet in the HZ of stars somewhat more massive than the Sun (i.e., HZ in an asteroid belt). Assuming that larger Jupiterlike planets will be discovered first, it will then be possible to assess the long-term dynamical stability of planetary orbits located within the HZ under the perturbative influence of the larger planet. If unstable, these systems could then be eliminated from the search. This may or may not be a problem for the numerous nearby M dwarfs (whose bolometric luminosities are typically two or three orders of magnitude less than the Sun's), since any Jupiterlike planets in these systems are likely to be much closer to the HZ in absolute distance. Prior to the anticipated discovery of Jupiterlike planets, similar long-term dynamical calculations could also be performed for HZ orbits in both accretion-modeled planetary systems (Wetherill 1996) and known nearby binary star systems. Disk accretion modeling of isolated M dwarf planetary systems might suggest whether these systems are sufficiently stable from large planet perturbations to be likely candidates in the search for a habitable planet. In previous three-body calculations of planetary orbit stability in binary systems, the planet was implicitly the most massive one in the system. This would likely be a Jovian planet rather than a potentially habitable planet. For the investigation of the stability of habitable planets in binary systems, four-body experiments are needed.

As previously noted, the results of Haberle et al. suggest that even a modest atmosphere may be sufficient to prevent water and other volatiles from freezing out on the dark hemisphere of a synchronously rotating planet in the HZ of a late K or M star. As the authors conclude, these results are encouraging but need to be substantiated by more sophisticated modeling of atmospheric heat transport.

REFERENCES

ARTYMOWICZ, P., C.J. CLARKE, S.H. LUBOW, AND J.E. PRINGLE (1991), "The Effect of an External Disk on the Orbital Elements of a Central Binary," *ApJ* **370:** L35–L38.

AUMANN, H.H., F.C. GILLETT, C.A. BEICHMAN, T. DEJONG, J.R. HOUCK, F.J. LOW, G. NEUGEBAUER, R.G. WALKER, AND P.R. WESSELIUS (1984), "Discovery of a Shell Around Alpha Lyrae," *ApJ* **278:** L23–L27.

BACKMAN, D.E., AND F. PARESCE (1993), "Main Sequence Stars with Circumstellar Solid Material: The Vega Phenomenon," in *Protostars and Planets III*, E.H. Levy et al., eds. (Tucson: University of Arizona Press), pp. 1253–1304.

BARROW, J.D., AND F.J. TIPLER (1986), *The Anthropic Cosmological Principle* (Oxford: Oxford University Press).

BODENHEIMER, P. (1989), "The Impact of Stellar Evolution on Planetary System Development," in *The Formation and Evolution of Planetary Systems*, H.A. Weaver and L. Danly, eds. (Cambridge: Cambridge University Press), pp. 243–273.

*BURNS, J.A. (1986), "The Evolution of Satellite Orbits," in *Satellites*, J.A. Burns and M.S. Matthews, eds. (Tucson: University of Arizona Press), pp. 117–158.

CALDEIRA, K., AND J.F. KASTING (1992), "Susceptibility of the Early Earth to Irreversible Glaciation Caused by Carbon Dioxide Clouds," *Nature* **359:** 226–228.

CAMERON, A.G.W. (1963), "Stellar Life Zones," in *Interstellar Communication*, A.G.W. Cameron, ed. (New York: W.A. Benjamin), pp. 107–114.

CARTER, B. (1983), "The Anthropic Principle and Its Implications for Biological Evolution," *Phil. Trans. R. Soc. Lond. A* **310:** 347–363.

COUNSELMAN, C. (1973), "Outcomes of Tidal Evolution," *ApJ* **180:** 307–314.

DELSEMME, A.H. (1991), "Origin of the Biosphere of the Earth," in *Bioastronomy: The Search for Extraterrestrial Life*, J. Heidmann and M.J. Klein, eds. (Berlin: Springer-Verlag), pp. 117–123.

*DOBROVOLSKIS, A.
Spin Evolutio

DOLE, S.H. (1964),
Company).

DOYLE, L.R., R. VI
"Circumstellar
Stars. II. Obse
Extraterrestrial

DOYLE, L.R., N.C.
"Stellar Mass
volume.

DUQUENNOY, A., A
Stars in the Sol
in an Unbiased

DVORAK, R. (1986),
A&A **167:** 379–

DVORAK, R., CH. FR
Planetary Orbit

FOGG, M.J. (1992), "
Habitable Plane

GOLDIN, D. (1994), "
Washington D.C

GOUGH, D.O. (1981),
Solar Phys. **74:** 2

GRAEDEL, T., I. SACK
Loss: A Potential
18: 1881–1884.

GRAZIANI, F., AND D.
Nature of Planet

HABERLE, R.M., C.P.
Synchronously Ro

HALE, A. (1994), "C
Implications for
306–332.

HALE, A. (1996), "Det
Binary and Multip

berle et al. suggest
nt to prevent water
rk hemisphere of a
ate K or M star. As
ging but need to be
of atmospheric heat

PRINGLE (1991), "The
s of a Central Binary,"

G, J.R. HOUCK, F.J. LOW,
(1984), "Discovery of a

Sequence Stars with
enon," in *Protostars and*
rsity of Arizona Press),

Cosmological Principle

volution on Planetary
olution of Planetary Sys-
e: Cambridge University

bits," in *Satellites*, J.A.
rsity of Arizona Press),

ty of the Early Earth to
de Clouds," *Nature* **359:**

Interstellar Communi-
njamin), pp. 107–114.

Implications for Biolog-
347–363.

on," *ApJ* **180:** 307–314.

e of the Earth," in *Bio-*
J. Heidmann and M.J.
3.

DOBROVOLSKIS, A. (1980), "Atmospheric Tides and the Rotation of Venus. II. Spin Evolution," *Icarus* **41:** 18–35.

DOLE, S.H. (1964), *Habitable Planets for Man* (New York: Blaisdell Publishing Company).

DOYLE, L.R., R. VIKRAMSINGH, D.P. WHITMIRE, AND N.C. HEATHER (1995), "Circumstellar Habitable Zones and Mass Loss from Young Solar-type Stars. II. Observational Considerations," in *Progress in the Search for Extraterrestrial Life*, ASP Conf. Ser., S. Shostak, ed., **74:** 195–204.

DOYLE, L.R., N.C. HEATHER, R. VIKRAMSINGH, AND D.P. WHITMIRE (1996), "Stellar Mass Loss and the Young Solar System Habitable Zone," this volume.

DUQUENNOY, A., AND M. MAYOR (1991), "Multiplicity Among Solar-type Stars in the Solar Neighborhood. II. Distribution of the Orbital Elements in an Unbiased Sample," *A&A* **248:** 485–524.

DVORAK, R. (1986), "Critical Orbits in the Elliptic Three-Body Problem," *A&A* **167:** 379–386.

DVORAK, R., CH. FROESCHLÉ, AND CL. FROESCHLÉ (1989), "Stability of Outer Planetary Orbits (P-Types) in Binaries," *A&A* **226:** 335–342.

FOGG, M.J. (1992), "An Estimate of the Prevalence of Biocompatible and Habitable Planets," *J. Brit. Interplanet. Soc.* **45:** 3–12.

GOLDIN, D. (1994), "Address to the 75th Anniversary Meeting of the AGU, Washington D.C.," *Nature* **369:** 349.

GOUGH, D.O. (1981), "Solar Interior Structure and Luminosity Variations," *Solar Phys.* **74:** 21–34.

GRAEDEL, T., I. SACKMANN, AND A. BOOTHROYD (1991), "Early Solar Mass Loss: A Potential Solution to the Weak Sun Paradox," *Geophys. Res. Lett.* **18:** 1881–1884.

GRAZIANI, F., AND D.C. BLACK (1981), "Orbital Stability Constraints on the Nature of Planetary Systems," *ApJ* **251:** 337–341.

HABERLE, R.M., C.P. MCKAY, D. TYLER, AND R.T. REYNOLDS (1996), "Can Synchronously Rotating Planets Support an Atmosphere?," this volume.

HALE, A. (1994), "Orbital Coplanarity in Solar-type Binary Systems: Implications for Planetary System Formation and Detection," *AJ* **107:** 306–332.

HALE, A. (1996), "Determining Habitable Planetary Environments Within Binary and Multiple Systems," this volume.

HART, M.H. (1978), "The Evolution of the Atmosphere of the Earth," *Icarus* **33:** 23–39.

HART, M.H. (1979), "Habitable Zones Around Main Sequence Stars," *Icarus* **37:** 351–357.

HUANG, S.-S. (1960), "Life Outside the Solar System," *Sci. Am.* **202 (4):** 55–63.

✱ IBEN, I. (1967a), "Stellar Evolution Within and Off the Main Sequence," *Ann. Rev. Astron. Astrophys.* **5:** 571–626.

IBEN, I. (1967b), "Stellar Evolution. VI. Evolution from the Main Sequence to the Red Giant Branch for Stars of Mass 1 $M_\odot$, 1.25 $M_\odot$ and 1.5 $M_\odot$," *ApJ* **147:** 624–649.

IBEN, I. (1974), "Post Main Sequence Evolution of Single Stars," *Ann. Rev. Astron. Astrophys.* **12:** 215–256.

IBEN, I., AND A. RENZINI (1983), "Asymptotic Giant Branch Evolution and Beyond," *Ann. Rev. Astron. Astrophys.* **21:** 271–342.

ISAACMAN, R., AND C. SAGAN (1977), "Computer Simulation of Planetary Accretion Dynamics: Sensitivity to Initial Conditions," *Icarus* **31:** 510–533.

KASTING, J.F. (1988), "Runaway and Moist Greenhouse Atmospheres and the Evolution of Earth and Venus," *Icarus* **74:** 472–494.

KASTING, J.F. (1991), "CO_2 Condensation and the Climate of Early Mars," *Icarus* **94:** 1–13.

KASTING, J.F. (1996), "Habitable Zones Around Stars: An Update," this volume.

KASTING, J.F., O.B. TOON, AND J.B. POLLACK (1988), "How Climate Evolved on the Terrestrial Planets," *Sci. Am.* **258 (2):** 90–97.

✱ KASTING, J.F., D.P. WHITMIRE, AND R.T. REYNOLDS (1993), "Habitable Zones Around Main Sequence Stars," *Icarus* **101:** 108–128.

KUBALA, A., D. BLACK, AND V. SZEBEHELY (1993), "Stability of Outer Planetary Orbits Around Binary Stars: A Comparison of Hill's and Laplace's Stability Criteria," *Celest. Mech. Dyn. Astron.* **56:** 51–68.

LAZZARO, D., B. SICARDY, F. ROQUES, AND R. GREENBERG (1994), "Is There a Planet Around β Pictoris? Perturbations of a Planet on a Circumstellar Dust Disk. 2. The Analytical Model," *Icarus* **108:** 59–80.

LECAR, M., J.C. WHEELER, AND C.F. MCKEE (1976), "Tidal Circulation of the Binary X-Ray Sources Hercules X-1 and Centaurus X-3," *ApJ* **205:** 556–562.

LISSAUER, J.J. (1989), "Which Stars Have Planets?," in *The Formation and Evolution of Planetary Systems*, H.A. Weaver and L. Danly, eds. (Cambridge: Cambridge University Press), pp. 304–308.

LISSAUER, J.J. (
Planetary S

LOVELOCK, J.E.,
and Climate

MCKAY, C.P., AN
Early Mars,

O'DELL, R., AND

✱ PEALE, S.J. (1977)
Satellites, J.A

PENDLETON, Y.J.,
the Onset of
88: 1415–14

POLLACK, J.B., AN
Contraction
Icarus **21:** 24

POLLACK, J.B., J.F.
Case for a W

POLLARD, W.G. (1
653–659.

RABL, G., AND R. D
Stars: A Num

REYNOLDS, R.T., S.
the Habitabili

REYNOLDS, R.T., C
Heated Ocean
Res. **7:** 125–13

ROOD, R.T., AND J.
Extraterrestrial

ROQUES, F., H. SCH
Around β Pic
Disk. 1. The N

✱ SACKMANN, I.-J., A.
Present and Fu

SAGAN, C., AND C. C
on Early Earth

nere of the Earth," *Icarus*

n Sequence Stars," *Icarus*

" *Sci. Am.* **202 (4):** 55–63.

ne Main Sequence," *Ann.*

om the Main Sequence to
, 1.25 $M_\odot$ and 1.5 $M_\odot$,"

Single Stars," *Ann. Rev.*

nt Branch Evolution and
-342.

Simulation of Planetary
nditions," *Icarus* **31:** 510–

use Atmospheres and the
-494.

Climate of Early Mars,"

Stars: An Update," this

How Climate Evolved on

(1993), "Habitable Zones
–128.

ability of Outer Planetary
of Hill's and Laplace's
56: 51–68.

NBERG (1994), "Is There a
Planet on a Circumstellar
8: 59–80.

"Tidal Circulation of the
aurus X-3," *ApJ* **205:** 556–

?," in *The Formation and*
and L. Danly, eds. (Cam-
08.

Lissauer, J.J. (1995), "Urey Prize Lecture: On the Diversity of Plausible Planetary Systems," *Icarus* **114:** 217–236.

Lovelock, J.E., and A.J. Watson (1982), "The Regulation of Carbon Dioxide and Climate," *Planet. Space Sci.* **30:** 795–802.

McKay, C.P., and W.L. Davis (1991), "Duration of Liquid Water Habitats on Early Mars," *Icarus* **90:** 214–221.

O'Dell, R., and Z. Wen (1994), As reported in *Sci. News* **145:** 391.

⊛ Peale, S.J. (1977), "Rotation Histories of the Natural Satellites," in *Planetary Satellites*, J.A. Burns, ed. (Tucson: University of Arizona Press).

Not at UCI
but check anyway

Pendleton, Y.J., and D.C. Black (1983), "Further Studies on the Criteria for the Onset of Dynamical Instability in General Three-Body Systems," *AJ* **88:** 1415–1419.

Pollack, J.B., and R.T. Reynolds (1974), "Implications of Jupiter's Early Contraction History for the Composition of the Galilean Satellites," *Icarus* **21:** 248–253.

Pollack, J.B., J.F. Kasting, S.M. Richardson, and K. Poliakoff (1987), "The Case for a Wet, Warm Climate on Early Mars," *Icarus* **71:** 203–224.

Pollard, W.G. (1979), "The Prevalence of Earthlike Planets," *Amer. Sci.* **67:** 653–659.

Rabl, G., and R. Dvorak (1988), "Satellite-Type Planetary Orbits in Double Stars: A Numerical Approach," *A&A* **191:** 385–391.

Reynolds, R.T., S.W. Squyres, D.S. Colburn, and C.P. McKay (1983), "On the Habitability of Europa," *Icarus* **56:** 246–254.

Reynolds, R.T., C.P. McKay, and J.F. Kasting (1987), "Europa, Tidally Heated Oceans, and Habitable Zones Around Giant Planets," *Adv. Space Res.* **7:** 125–132.

Rood, R.T., and J.S. Trefil (1981), "Are We Alone?," in *The Possibility of Extraterrestrial Civilizations* (New York: Scribner Publishing Company).

Roques, F., H. Scholl, B. Sicardy, and B.A. Smith (1994), "Is There a Planet Around β Pictoris? Perturbations of a Planet on a Circumstellar Dust Disk. 1. The Numerical Model," *Icarus* **108:** 37–58.

⊛ Sackmann, I.-J., A.I. Boothroyd, and K.E. Kraemer (1993), "Our Sun. III. Present and Future," *ApJ* **418:** 457–468.

QB1
A9 Drum

Sagan, C., and C. Chyba, "Organic Shielding of UV-Labile Greenhouse Gases on Early Earth and Mars," abstract, this volume.

Schwartzman, D.W., and T. Volk (1989), "Biotic Enhancement of Weathering and the Habitability of Earth," *Nature* **340:** 457–460.

Smith, B.A., and R.J. Terrile (1984), "A Circumstellar Disk Around Beta Pictoris," *Science* **226:** 1421–1424.

Solomon, S.C., and J.W. Head (1991), "Fundamental Issues in the Geology and Geophysics of Venus," *Science* **252:** 252–260.

Szebehely, V., and R. McKenzie (1981), "Stability of Outer Planetary Systems," *Celest. Mech.* **23:** 3–7.

Walker, J.C.G., P.B. Hays, and J.F. Kasting (1981), "A Negative Feedback Mechanism for the Long-Term Stabilization of Earth's Surface Temperature," *JGR* **86:** 9776–9782.

Wetherill, G.W. (1991), "Occurrence of Earth-like Bodies in Planetary Systems," *Science* **253:** 535–538.

Wetherill, G.W. (1994), "Possible Consequences of Absence of 'Jupiters' in Planetary Systems," *A&SS* **212:** 23–32.

Wetherill, G.W. (1996), "The Formation of Habitable Planetary Systems," this volume.

Whitmire, D.P., J.J. Matese, and L.J. Tomley (1988), "A Brown Dwarf Companion as an Explanation of the Asymmetry in the beta Pictoris Disk," *A&A* **203:** L13–L15.

Whitmire, D.P., R.T. Reynolds, and J.F. Kasting (1991), "Habitable Zones for Earth-like Planets Around Main Sequence Stars," in *Bioastronomy: The Search for Extraterrestrial Life,* J. Heidmann and M.J. Klein, eds. (Berlin: Springer-Verlag), pp. 173–178.

Whitmire, D.P., L.R. Doyle, R.T. Reynolds, and J.J. Matese (1995a), "Circumstellar Habitable Zones and Mass Loss from Young Solar-type Stars. I. Theory," in *Progress in the Search for Extraterrestrial Life,* ASP Conf. Ser., S. Shostak, ed., **74:** 183–193.

Whitmire, D.P., L.R. Doyle, R.T. Reynolds, and J.J. Matese (1995b), "A Slightly More Massive Young Sun as an Explanation for Warm Temperatures on Early Mars," *JGR* **100:** 5457–5464.

Zahn, J.-P. (1977), "Tidal Friction in Close Binary Stars," *A&A* **57:** 383–394.

DETERM
ENVI
A

So

The presence o
complicates the
planetary envirc
question whether
that they can, o
of planetary orb
theoretical studi
exist in binary
either close toge
varying insolatic
varying distance
difficult to quan
stability criteria
planet are minim
of dissimilar
component(s) ma
the less massive

INTRODUCTIO

Most stu
habitable planeta
System or on sta
and many of th
Galaxy are not. R
that approximate

CIRCUMSTELLAR HABITABLE ZONES

PROCEEDINGS OF THE FIRST INTERNATIONAL CONFERENCE

Edited by Laurance R. Doyle

Introduction by Carl Sagan

TRAVIS HOUSE PUBLICATIONS MENLO PARK, CALIFORNIA

Travis House Publications
P. O. Box 37
Menlo Park, CA 94026
1 800 96-TRAVIS

Printed in the United States of America
00 99 98 97 96 9 8 7 6 5 4 3 2 1

Editing and Design, Ellen Blue
Typography, Vilma Zamora
Proofreading, Ron Bemaul and Ellen Blue

Library of Congress Cataloging-in-Publication Data

Circumstellar habitable zones : proceedings of the first international conference / edited by Laurance R. Doyle : introduction by Carl Sagan.
p. cm.
Includes bibliographical references.
ISBN 0-9650896-0-6
1. Life on other planets—Congresses. 2. Exobiology—Congresses.
3. Circumstellar matter—Congresses. I. Doyle, Laurance R.
(Laurance Reeve), 1953– .
QB54.C56 1996
577'.099—dc20 96–12702
CIP

ISBN 0-9650896-0-6

To all the participant
tectonic plates and oce
swimming, jumping,
photosynthesizing—m
through the Universe t