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# A Consistent Model of Terrestrial PlanetMagnetospheres and Rotations in Our Solar System

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**ABSTRACT**

TheSuncomprises99.9%ofthesolarsystemmasssoitisexpectedthatSunterrestrialplanetinteractionscaninfluencethemotionaswellastherotationof the terrestrial planets. Gravity affects the planet orbital motions while thechanging magnetic fields of the Sun can influence the planet rotations. Pla-netsthatmanifestamagneticfielddominateanyweakermagneticfieldsfromtheSun,buttherotationofterrestrialplanetswithoutamagneticfieldinteractswiththechangingSun'sfielddependentontheelectricalconductivityofthecoreregion.Itisdeterminedthattheaverageplanetdensitybecomesausefulquantitytodescribethemagneticstateofaterrestrialplanet.Anaveragedensityof5350 ±50kg/m$^3$ishypothesizedtoseparateplanetsthatdevelopmag-netospheres from those that do not. Planets with higher average densities,Mercury and Earth, developed magnetospheres. While those with lower average densities, Venus and Mars never developed magnetospheres. Terrestrialplanetswithmagnetospheresaretheonestoalsoexhibitplatetectonics.ThesmallsizeofMercuryledtoMercuryonlyexhibitingafrozeninmagnetization of potentially magnetic regions. The lack of magnetospheres as well aslack of plate tectonics prevented the continual transfer of core heat to thesurface that limited the surface vulcanism to an initial phase. For Venus, itmeantthatthesurfaceregionswouldonlysporadicallyconvulse.Inthispicture,theapparentanomalousaxialrotationofVenusisanaturalconsequenceoftherotationoftheSun.ForMarswithrelativelylowsurfacetemperatures,itmeantthattherewaslittleheatexchangethroughthecrustthatwouldallowthe lower crust to retain large amounts of water. For Mars to have initiallyhad flowing liquid water required that the atmosphere at that time containedhigh concentrations of infrared absorbing gases at least as compared to thepresentlevelofinfraredabsorbinggasesontheEarth.Theterrestrialplanetshaveironbasedcoresbecauseironhasthehighestbindingenergypernucle-on that can be made in the steady state lives of massive stars no matter howmassive. This suggests that many of the conclusions reached here may also beapplicabletoexoplanets.

**Keywords:**Earth,Mercury,Venus, Mars,Magnetic FieldsSun,Early Solar System,PlateTectonics

## I. INTRODUCTION

In a recent publication, it was shown that the Earth acquired an anomalouslyhigh average density as a result of a collision between a pre-Earth and anotherobject that was near the orbit of the pre-Earth [1]. This collision was extremelyviolent in that the object that became the Earth wound up with a major portionof the more massive and also radioactive elements. An indication of this is thattheobservedisotopicratiosoftheEarthandwhatthenbecamethemoonshouldbethesame[2].AsthedebrisfieldmovedoutbeyondtheRochelimit,themoonformedasanelongatedmasssothatitorbitedtheEarthwiththesameside fac-ing the Earth as it gradually migrates out away from the Earth. From the after-math of this collision, the Earth Moon system was the result. In that previouspublication, some results from the Earth Moon formation were discussed. AprincipalresultwasthattheEarthacquiredananomalouslyhighaveragedensitythat led to Earth exhibiting a sizeable magnetosphere. This magnetic field al-lowedthedevelopmentofplatetectonicsmakingpossiblelong-termbillion-yearstability.Suchlongtermstabilityisgenerallyrecognizedasbeingnecessaryforthedevelopmentofcomplexlifeforms.Inthispublication,someconsequencesand possible generalizations to other terrestrial planets will be discussed. SinceEarthhasamagneticfield,thegeneraltendencyistoassume,thatotherplanetsstartedoutwithamagneticfieldthatwasthensubsequentlylostduetoquirksofdevelopment. The objective of this paper is to show that there is a pivotal linkbetween the details of the Sun to planet interaction, the rotation of the planets,and whether a terrestrial planet manifests a magnetosphere. It should be notedthattheSuncomprises99.9%oftheentiresolarsystemmasssothatSunplanetinteractionscanbeexpectedtobe important.TheSuninteractswiththeplanetsmainly through gravity, but the Sun also interacts with the various planetsthroughtheSun'schangingmagneticfields.TheSunhasbothadipolarmagnet-ic field that is currently changing polarities about every 11 years and radialcomponents associated with solar wind and the Parker spiral. The interactionwiththecomparativelyweakfieldsfromtheSundependsuponwhetherthepla-nethasamagneticfieldofitsownandtheelectricalconductivityofanycorere-gions.ThisisbecauseLenz'slawstatesthatcurrentsinaconductorwillalwaysbegeneratedtoopposeanymagneticfluxchanges.

A key goal of this paper is to examine some of the reasons that a terrestrialplanetexhibitsamagneticfield.Theterrestrialplanetshaveironbasedcoressinceironhasthehighestbindingenergythatcanbemadeinthesteadystate-lives of massive stars. Iron is then especially abundant in the cores of terrestrialplanets far and wide. Iron is expected to be a widely common element in thecosmos. Our solar system is just one example of a solar system formed under thegeneral nebular theory of solar system formation. [3] [4] This suggests that theconclusions reached here are also applicable to exoplanets currently being dis-covered.

## II. RESULTSANDDISCUSSION

For a terrestrial planet to exhibit a magnetic field there is a general understand-ing that there must be a molten outer core region and sufficient rotation so thatcurrentscanthroughconvectiveactiongenerateamagneticfield.Forterrestrialplanets the major core elements are iron and some combination of nickel andother metallic elements. Iron acquired its universal abundance because it is themost massive element that can be made in the steady state lives of the cores ofmassive stars no matter how massive. Iron is generally regarded as a ferromag-neticelement,butforthepurposeofgeneratingamagneticfieldfortheearththekeythingisthatitcanactasanelectrical conductor.Similarlycurrentsinacoilofcopperwirescangenerateamagneticfieldeventhoughcopperitselfisnotamagneticelement.Agoalofthispaperistoparameterizethefactorsthatleadtoaconsistentpictureofthemagnetospheresofthefourterrestrialplanetsandthemooninthesolarsystem.Itshouldbenotedthatoursolarsystemhaswhatmaybe termed a friendly Jupiter so that the general placement and development ofthe terrestrial planets has not been seriously altered since the formation of thesolarsystem.Thekeydriverforthedevelopmentandevolutionoftheterrestrialplanetswasandistheupwellingof heatfrominteriorregions.Thecoreregionofa terrestrial planet comprises only a small fraction of its total mass. For theEarth, for example, it will be shown that the mass fraction within a sphereone-fourthoftheEarthradiusisjust2%oftheEarth'stotalmass.Buttheupwel-lingofheatfromthatsmallfractionofthetotalmassisextremelycrucialfortheEarth'smagnetosphere.**Table 1**containssomeusefulrelevantdatafortheterre-strialplanetsasasubsetofNASAdatatables[5].

Theterrestrialplanetsinoursolarsystemformedinthepresenceofathermalgradient with higher temperatures occurring nearer the Sun. The Sun and theplanetshadacommonformationtimeof4.6billionyearsago.AsstatedearliertheSuncomprises99.9%ofthemassinthesolarsystem.AsshowninRef.1theaverage density of the terrestrial planets Mercury, Venus, and Mars follow asmooth curve with the Earth Moon system being anomalous because of theEarthformationprocess.Usefulparametersforcharacterizingtheevolutionofaterrestrialplanetmightincludethetotalmass,themassandradioactiveelementconcentrationasaheatsource,theaverageplanetdensity,andsomemeasureof

**Table1.**NASAterrestrialplanetdetails.Onlyasubsetoflistingsareincludedhere[3].

| Planet | Mass (Earth=1) | Semimajor OrbitRadius(AU) | Eccentricity | Orbit Period (Solar Days) | Rotation Period(SolarDays) | Axial Tilt Angle(°) | Average DensityAn (Earth=1) |
|---|---|---|---|---|---|---|---|
| "Sun" | 332,000 | | | | 25 to 30days athigher latitudes | | 0.254 |
| Mercury | 0.055 | 0.39 | 0.206 | 88.0 | 58.6(3:2 orbital torotationlocking) | 0.03 | 0.98 |
| Venus | 0.82 | 0.72 | 0.007 | 224.7 | −243.0 | 2.64 | 0.95 |
| Earth | 1 | 1.00 | 0.017 | 365.26 | 0.9973 | 23.45 | 1.00 |
| Mars | 0.11 | 1.52 | 0.093 | 686.9 | 1.026 | 25.2 | 0.71 |
| Jupiter | 317.8 | 5.20 | 0.048 | 11.86 tropical years | 0.41 | 3.13 | 0.241 |
| "Moon orbit about Earth" | 0.012 | $2.567\times10^{-3}$ | 0.055 | 27.32 | 27.32 | 5.2 relative to Earthorbit | 0.61 |

theplanetelectricalconductivityofacoreregionasameansofinteractingwiththeSunthroughtheSun'smagneticfield.Terrestrialplanetsareexpectedtoex-hibit gravitational differentiation so that more dense regions sink to the interiorregions.**Figure 1**showstheaveragedensityoftheterrestrialplanetsasshowninRef. 1. The Earth acquired an anomalously high density as a result of theEarth-Moonformationprocessasalsoshownin**Figure1**.

Fairly recent publications have presented measurements and modeling of thedensityoftheEarthasafunctionofthedepthintotheEarth[6][7].Thesemea-surements can be recast to represent density as a function of the radius of theEarthbysubtractingthedepthfromtheEarthaverageradius=6371km.**Figure2**shows the density of the Earth as a function of the radius from the center.Thereisadensitydropinmovingoutwardfromtheinnercoretotheoutercore.This is interpreted as a transition from a solid inner core to a fluid outer core.There is also a fairly rapid decrease in moving outward from the outer core tothelowermantle.

**Table2**showstheintegralofthedensityforthedifferentregionsoftheEarth.Even though the core density rises to about 13.1 times the density of water thetotalmassfractionwithinthisregionisonlyabout0.017ofthetotalmass.Thisoccursfortworeasons.Oneisthateventheoutermostregionsthedensityisstill 3 to 4 times the density of water. And reason two is that the volume of asphere is a steep function of radius being proportional to radius cubed. Inte-gratingouttotheEarth'ssurfacegivesthetotalEarthmassof$5.97\times10^{24}$kg.

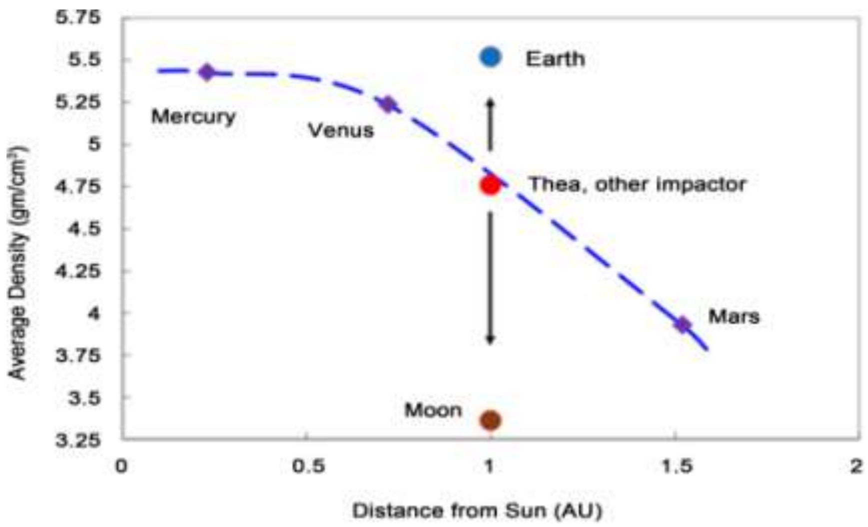


**Figure 1.** The dotted line shows the variation in the average terrestrial planet density asa function of the distance from the Sun [1]. The anomalous earth and moon averagedensitiesare also indicated.

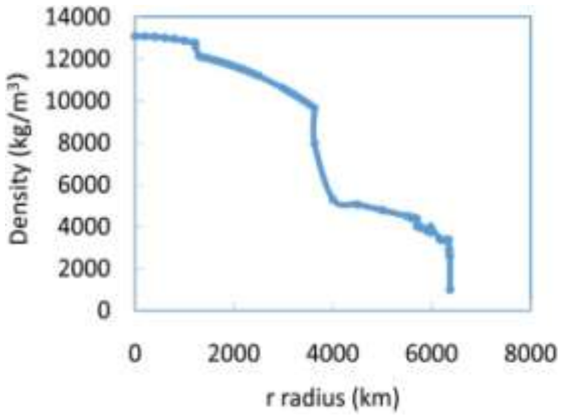


**Figure2.**ThedensityoftheEarthasfunctionofradiusis shownas determined from thedata in[4]and[5].

Dividing the total mass by the Earth volume gives an average Earth density =5515kg/$m^3$.ItisinterestingtonotethatEarthdensityasafunctionofrdoesnotfalltothislowaleveluntilr≈0.63$R_E$. ForEarth,planetrotation,andrisingheatconvectionproducescurrentsinthefluidoutercorethatproducesamagneticfield.Thiscontinuousrisingheatasso-ciatedwiththemagneticfieldiswhatdrivesplatetectonicsonEarth.TheEarthhassufficientsizesothatthesupplyofheatprovidedbytheoriginalcompactionenergyplusthatfromradioactivedecaysisexpectedtolasttheforeseeabletimescaleassetbythestabilityoftheSun[8].Thehalf-lifefortheradioactivedecayof$U^{238}$is4.5Billionyearssohalfoftheoriginal$U^{238}$stillremainsnow. Eachoftheterrestrialplanetsaswellasthemoonhasacoreregioncomposed

| Region | Radius(km) | | Integrated Mass ($10^{24}$kg) | MassFraction% |
|---|---|---|---|---|
| | Density(kg/m³)InnerCore | 0-1221.5 | 0.09992 | 1.674 |
| | 13,088.5 | | 1.887 | 31.608 |
| | | [illegible] | 0.1504 | 2.5193 |
| OuterCore | 1221.5-3480.0 | 12,500.0 $-5.347\times10^{-4}\times(r-1221.5)^2$ | 0.482 | 8.074 |
| Lower Mantle | 3480.0-3600.0 | 7956.5 | | |
| Mantle | 3600.0-4000.0 | 7956.5 $-6.57\times(r-3600)$ | 3.1996 | 53.590 |
| Mantle | 4000.0-6200.0 | 5200 $-4.1729\times10^{-4}\times(r-4000)^2$ | 0.1568 | 2.626 |
| Crust | 6200-6371 | 2690 $-9.766\times(r-6200)$ | Total mass =5.975 | 100.09 |

**Table2.**Earthregionsdensitiesandmassfractions.REarth=6371km.MassofEarth=

largely of iron, but the core regions differ in their temperatures and pressures.Consequently, the cores differ in the phases from partially solid and fluid withthedensersolidcorebeingsurroundedbyalowerdensityfluid.Lowerpressuresdue to either lower mass compacting the planet or lower temperatures can pro-duce either fluid cores or solidified cores. The phase diagram of iron has beenmeasured so that the Earth core temperature and pressure profiles are well es-tablished[9].TheEarth'smagneticfieldisdefinitelyassociatedwiththecorere-gion.TheEarth'smagneticfieldpoleshavebeenmeasuredtoflipontheorderofhalfamillionofyearsindicatingtheEarth'scoremustbeamainfactortohavesuch a long period [10]. The mantle contains nearly 2/3 rds of the total mass asshown in **Table 2**. The composition of the mantle for each of the terrestrial pla-netsandthemoonshouldbelargelysimilar.
Beforeconsideringthedetailsofanyparticularterrestrialplanetitisusefultoconsidersomeoftheircommonformationelements.EarthexperiencedaperiodknownastheHadeanEonfromformationtimetoabout700millionyears[11].In this time before the start of life similar developments should have happenedontheotherterrestrialplanets.EachoftheterrestrialplanetsformedasapartoftheformationoftheSun.EachactedtocompactthemassatsomedistancefromtheSunwithsufficientheattocausegravitationaldifferentiation.Eachthenex-perienced a period of volcanoes causing surface disruptions. Volatile constitu-ents such as water were largely boiled away from the surfaces of the formingplanets. It is uncertain what fraction of water was returned via comets versusfromoutgassingfromdeeperwithintheEarth.Thefractionreturnedviacometsisgenerallyheldtobeasizableamountfrom10%to100%.EvidenceisthatthesurfaceoftheEarthwasentirelycoveredbyliquidwaterearlyinitshistory[10].

ThiswasprobablytrueforatleasttheplanetsVenus,EarthandMars.
Eachterrestrialplanetsharedatimeperiodofrapidbombardmentearlyinthehistoryofthesolarsystem.Eachbodywasinterceptedbyagreatnumberofwa-ter bearing comets in proportion to the cross section of the planet. The crosssection, $\pi R^2$, and the surface area, $4\pi R^2$, are both proportional to the radiussquaredsothereistheinitialexpectationthattheoceandepthcontributionfromcomet impacts on the different planets would initially be the same. The timescale for this initial bombardment and acclimation phase is expected to be cer-tainly less than a billion years. Each of the planets whether from initial planetoutgassing,orfromcometbombardment,wasinitiallycoveredinwater.Eachofthe planets then lost or retained an initial water covering at a rate dependent onthe planet distance from the Sun and energy evolution. For Earth rudimentarylife is generally thought to arise by about a billion years. Since no evidence of lifeonanyotherterrestrialplanethasbeenobserved,processesthatcausethediffe-rentiation of development on the different terrestrial planets had become effec-

tiveonthedifferentplanets.Thisisprobablyaperiodlongenoughforgeologicrelaxation, but not long enough for the development of any but the earliestforms of life. Early in the Sun's history the luminosity was only about 70% of thecurrent value [1]. To explain how the Earth could have been warm enough tohaveliquidflowingwatertwoitemsaregenerallythoughttohavebeenpresent.One is that there was enough water present to have largely covered the Earth'ssurface [12]. Water reflects less sunlight than land areas so that the lowered al-bedo causes greater heat absorption. The second is that there is expected to be$CO_2$outgassingassociatedwithvulcanismandsurfacedisruptions[13].Eachofthe terrestrial planets would have experienced a greater amount of heating duetowatercoveringmostofthesurfacesinitially.Mars,inparticular,shouldhavehad aninitialperiodofwatercoverageandlargesurfacedisruptions.EvenMer-curyandVenuswouldhavehadaninitialperiodofwatercoverageandsurfacechanges.ForEarththisperiodofinitial planetdevelopmentiscalledtheHadeanEonandlastedabout0.7billionyears[11].Howlongsuchaperiodlastedont heother terrestrial planets is much less certain and starts to depend on planet de-tails.

Marsshowsevidenceofflowingwaterearlyinitshistory.Anexaminationofthe conditions for Mars to have surface temperatures high enough for flowingliquidwatercanbeobtainedbyexaminationoftheenergybalancecomingfromtheSunandthatradiatedbyMars.EarlyontheSunhadaluminosityonlyabout70%ofitscurrentvalue[1].Thebasicconditionforaplanettohaveacoveringofliquidwateristhattheplanetsurfacetemperaturebegreaterthan273K.

The equation below simply states that the energy received by a planet mustequaltheradiatedenergyfortheplanettomaintainthetemperatureT.

$$x \cdot L \cdot \frac{\pi R_p^2}{4\pi D_{S-p}^2} \cdot (1-a) \cdot (1+\tau) = 4\pi R_p^2 \cdot \sigma \cdot T_p^4$$

L=presentLuminosityoftheSun,x·L=fractionofpresentSun'sLuminosity.

$R_p$=planetradius,$D_{S\text{-}p}$=distanceSuntoplanet.
a=planetalbedoequaltofractionofincomingenergyreflectedbacktospace,τ=numberoftimesinfraredwavelengthsareabsorbedintraversingtheplanet'satmosphere,σ=Stefan-Boltzmannconstant,$T_p$=planetsurfacetemperature.

For **Figure3**x·L has been chosen to be 70% of the Sun's luminosity torepresent the luminosity early in the lifetime of the Sun. The factor a has beenchosentobe0.30whichisclosetothepresentalbedooftheEarth.Analbedoof 0.3 can result from either some clouds or some partial reflective covering fromsnow or ice. It is probably a reasonable value. At the present time, x = 1, for theEarth using a = 0.30 and τ = 1.00 gives the average surface temperature for theEarth. At the present time for Venus using a = 0.70 and τ = 70 gives the averagesurface temperature for the planet Venus. The quantity τ is often called the "ab-sorptionlength"eventhoughitdoesnothavethedimensionsofatruelength.Theprincipalinfraredabsorbing,greenhouse, gasesarewatervapor,carbondioxide, and methane. Diatomic gasses such as $N_2$ and $O_2$ do not appreciablycontribute toTau since they are not strong infraredabsorbers.All ofthe differ-entgasescontributetothermaltransferprocessesasexpressedbytheidealgaslaw.

These calculations indicate that for Mars to have had liquid water on its sur-faceaminimumTauatleast4wasrequired.SinceatthepresenttimeforEarth,x=1,watervaporplusabout280ppm$CO_2$givesTau≈1,then$CO_2$levelsmusthave been about 4 times current Earth values to have had liquid water flowingon Mars early in its history. This is the case that Mars would have liquid waterbuttemperaturesbarelyabovethefreezingpointofwater.Thevaporpressureofwaterasafunctionoftemperatureisverynonlinear[1]sothatsurfaceevapo-ration would have been slow. Solar wind emanating from the Sun is generallycreditedwithslowlystrippingawaysurfacewaterandmostoftheatmosphereof

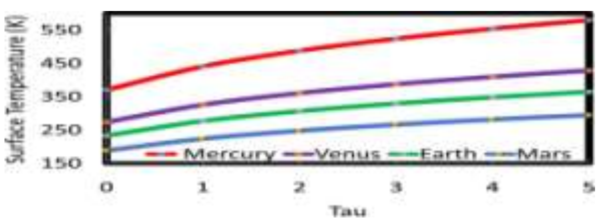


**Figure 3.** Early Faint Sun at 70% of current solar

luminosityenergybalancesurfaceplanettemperatures.Analbedoof0.30has been used for these calculations. Conditions of differentplanetaryatmosphereshavebeenindicatedduetovaryingab-sorption lengths. For each planet surface temperatures havebeen computed for different values of Tau. Water vapor andatmospheric$CO_2$aregenerallythemajorcontributorstoTau.

Mars[14].DuetotherelativelysmallsizeofMarsasvulcanismseizedtherewaslittlesourceofheattopromotefurther outgassingofwatertothesurface.SinceMars does not exhibit plate tectonics there was not a regular transfer of heatfromtheinteriorregionstothesurface.Sporadiclargescalevulcanismhasbeendetermined to have extended up to about 150 million years ago [15]. The time-scaleofMartianvulcanismisverylongsothatevensomefutureeventsmaybeexpected.ItisthereforeexpectedthatMarscouldhaveretainedlargeamountsofwaterbelowthesurfaceincrustalregions[16].

Theenergybalanceequationintheformpresentedisnotgenerallyapplicableto the planet Mercury, nor to the Moon, since these bodies do not have atmos-pheres. But early on during initial formation there would be a period of initialoutgassing and vulcanism in which Mercury would have had an initial atmos-phere. The high temperatures indicated for Mercury in **Figure 3**indicate thatthere would not have been a time of quiet oceans on Mercury but that a boilingstatewouldnaturallytendtooccur.

Venus is indicated to have been relatively warm early on so that there wouldhavebeenarapidtransferofwatertotheupperatmospherewhereitwouldhavebeenrapidlydissociatedbyultravioletlightfromtheSunleadingtoHescapingtospace.OverarelativelyshorttimeHandhencewaterwouldhavebeenlosttospace by this mechanism. The Venusian atmosphere would have then becomemoreandmoreenrichedincarbondioxideasvulcanismcontinued.Earthwouldhavehadamuchlowerrateofwatertransporttotheupperatmospheresincethevaporpressurecurveforwaterishighlynonlinear[1].Consequently,Earthstillhad a significant level of water even up to the time in which oxygen became asignificantcomponentoftheatmosphere,sothatozoneintheupperatmospherecouldlimittheescapeofHtospace. OxygenbecameasignificantpartofEarth'satmosphereonlyafterabouttwobillionyears[17].

An interesting question then is how the Earth would have to be changed sothat it would no longer exhibit a stable long term magnetic field. Any changethat eliminates the change in density between the inner core and outer corewould remove the conditions favoring a magnetic field. Since the inner corecomprises only 1.7% of the Earth's total mass the transition to a nonmagneticEarth can be facilitated with very little change in the total mass. In this regardtheaveragedensitythenbecomesaverygoodindicatoroftheplanets'behavior.Earth has the highest average density of the terrestrial planets. It was the basicconclusion of a previous paper that this was the result of the collision that re-sultedintheEarth-Moonsystem[1].Venushasamassslightlylessandaloweraverage density. Venus has no magnetosphere. It is postulated that an averagedensity greater than about 5350 ± 50 kg/m$^3$ is required for the maintenance of along-term magnetic field. On this basis Earth and Mercury should have startedout with magnetospheres and magnetic fields. There is the expectation thatEarth with its anomalously high average density and large size retained themagneticfield.ThesmallsizeofMercuryfacilitatedcorechangesovertimethatitisexpectedthatMercurywould presentlyexhibitafossilizedorfrozenout

magneticfield.VenusandMars,aswellastheMoon,thenneverdevelopedsta-blemagnetospheresormagneticfields.

TheSunexhibitsadipolarmagneticfieldassociatedwithconvectioncurrentsin the metallic hydrogen of the convection zone. Presently the dipolar field hasbeen reversing polarity about every 11 years. At the present time the equatorialregionoftheSunhasarotationperiodofabout24days withalongerperiodasthefieldbecomesmoreconcentratednearerthepolesuptoabout34days.Thisisanexampleof magneticbreakinginaction.ExtendingoutwardawayfromtheSun the Sun's magnetic field aided in transferring angular momentum awayfrom the Sun to the forming planetary system. The general rotation and ex-pected rotation of the Sun and of the various planets is illustrated in **Figure 4**.Viewed from above if the Sun is rotating anticlockwise then it is expected that alltheplanetsofthesolarsystemwouldalsobeorbitinganticlockwise.TherotationperiodoftheSun,currentlyabout24days,ismuchlessthantheorbitalrotationperiod of any of the planets. The daily axial rotation of the Earth is also in theexpecteddirectionasillustratedin**Figure4**.TheEarthhasamagnetospherethatlargely isolates the Earth from the weaker magnetic fields from the Sun. Thedominance of the Earth's magnetic field is indicated by the dotted circle sur-rounding the Earth in **Figure 4**. The most dramatic evidence for the action ofthe Earth's magnetic field is the aurora borealis due to charged particles ema-natingfromtheSunmovingtowardtheNorthandSouthpolesoftheEarth.ThesolarwindemanatingfromtheSunfoll owaxialmagneticfieldlinesawaythe

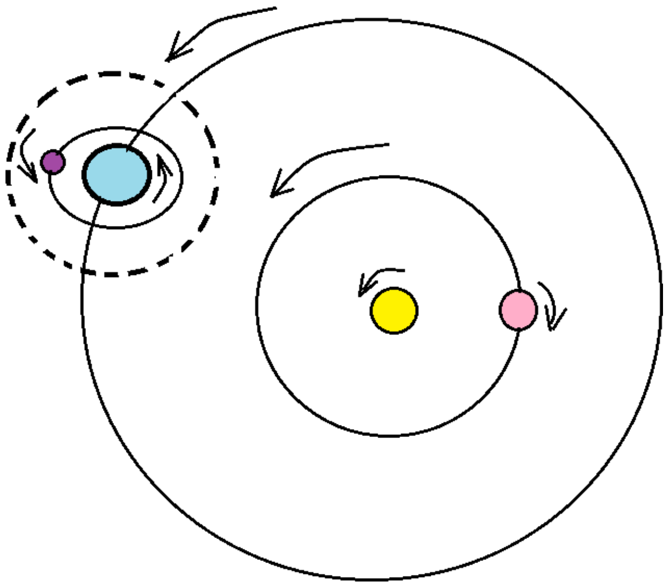

**Figure4.**Theorbitalrotationoftheplanets,EarthandVenus,andtheSunareindicated.TherotationperiodoftheSuniscurrentlyabout25days,butwasinitiallyshorter.VenusinteractsdirectlywiththeSunsmagneticfieldandrotatesclockwiseasitorbitstheSun in a counterclockwise direction. The Earth was shielded by itsownmagnetic fieldfrom the weaker rotatingmagnetic fieldfromtheSun.

Sun. The axial rotation of Mercury, although slow, and Marsare also in the expectedanticlockwisedirection.Venus,however,hasanaxialrotationthatisclockwise as indicated in **Figure 4**. The Sun has also a radial magnetic field asso-ciatedwiththesolarwind.

On this basis since Venus never developed a magnetosphere the metallicconducting core was directly subject to the magnetic field of the Sun. It shouldalsobenotedthattheearlySunwasthenrotatingatafasterratethanatpresentthatincreaseditsinteractionwith Venus.InitiallyarelativelyrapidrotatingSunemitted sufficient solar wind to blow outward the initial primordial hydrogenrich atmosphere from the inner solar system [18]. If the Sun was still rotatingtoo rapidly indications are that planets such as the Earth would not have beenabletodevelopstablesecondaryatmospheres.Itisarguedthatlifewasonlyableto develop on the Earth because of the Goldilocks rotation rate of the Sun. [18]TheSunhasbothadipolartimevaryingmagneticfieldaswellasaspirallyout-ward magnetic field that act to slow the rotation of Venus as well as draggingVenus as a poorly coupled gear. The dipolar field of the Sun presently reversesaboutevery11yearsandmayhavebeenashortertimeinthepastastheSunro-tation rate is also thought to have been faster. Lenz's law would then say thateddycurrentswouldbegeneratedinVenustomagneticallybraketherotationofVenus. The current directions for the eddy current loops indicated in **Figure 5**wouldbeinoppositedirectionsandthedirectionswouldreverseasthepolarities

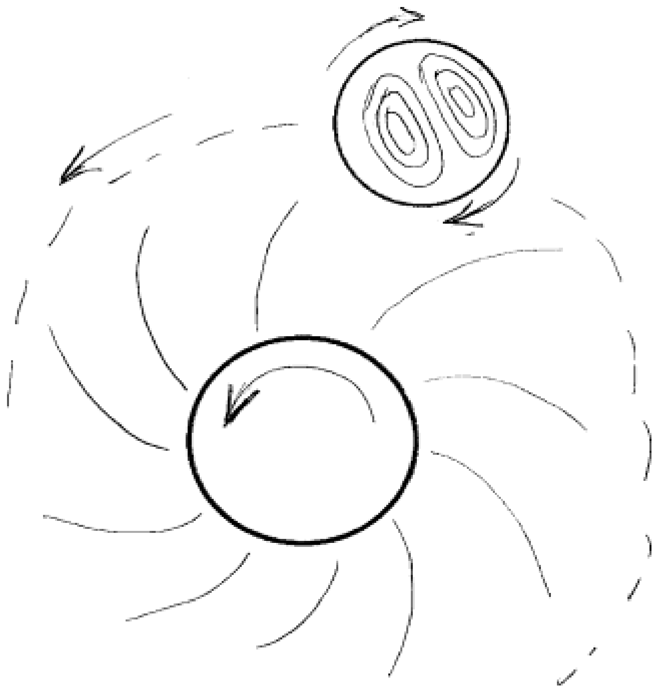

**Figure 5.** The relatively rapid rotation of the Sun and the nearlyredial magnetic field associated with the solar wind are indicated.Eddy currents in Venus that switch directions with the polarity re-versingdipolarfieldoftheSunareindicated.Theaxialrotationdi-rectionofVenusissetbythedraggingactionoftherotatingSun.

oftheSun'sdipolarfieldreverses.ThisisshowninFigure5.Theresultsshownhereareonlyqualitative.Furtherwork towardquantitativesolutionsisplanned.As indicated in **Table 1**there is a very small angle between the rotation axis ofbothMercuryandVenusandtheSun.Theseplanetsarethenideallyorientedtointeract with the rotation of the Sun. The radial component of the relativelyrapid rotating Sun drags the closer side of Venus forward resulting in a clock-wiserotationofVenusin**Figure5**.ItmayhelptovisualizetheSunasarotatinggearactingtospinVenus.Theclockwis erotationofVenusthennaturallyresultsfromtherotationoftheSun.TheEarth'smagnetosphereshieldstheEarth'sr o-tation from directly interacting with the weaker magnetic fields from the Sun.The Sun's magnetic field acted on each of the terrestrial planets dependent onthemagnetosphereoftheplanetaswellastheelectricalresistivityofthecore.

Mercury initially would have had a magnetosphere which shielded the mag-netic core of Mercury from the Sun's weaker magnetic field. The small size ofMercury leads to a cooling and solidifying of the core so that Mercury over acertain time frame lost the ability to generate a magnetic field of its own. Itshould then exhibit two manifestations of this. One should be a frozen in mag-netization of any magnetic deposits. Recent measurements made by the Mes-sengerspacecraftindicatethatMercuryexhibitedamagneticfielduptoabout4billion years ago [19]. The other should be that the metallic core of Mercurywould then interact with the changing magnetic fields of the Sun to brake anyrapid rotations of Mercury. The planet orbits have been approximated as circu-larwhichlimitsanydetailedanalysis,particularlyforMercury,whichexhibitsalargeeccentricityasshownin**Table 1**.

Further out in the solar system Mars red color indicates an incomplete diffe-rentiation.TheaveragedensityofMarsat3934kg/m$^3$isverylowtohaveahigh-ly electrically conducting core. The average density of Mars is well below thathypothesized to be required for a terrestrial planet to manifest a magnetic field.The behavior of Mars can then be reconciled with that of the other terrestrialplanets by Mars having a higher core resistivity to limit the generation of eddycurrents as a means of the planet interacting with the changing Sun's magneticfield.Marshasarelativelyrapidaxisrotationwithadaycurrentlyaboutequaltothat of the Earth. The rotation period of the Earth is increasing as the Moongradually moves away from the Earth. Initially a day on the Earth was muchshorter than that of a Mars day but at the present time each has a similar lengthof day [1]. Mars then exhibits a rotation rate that has largely remained un-changed since the formation of the early solar system. The axial rotation angleforMarsisrelativelylargeatabout25degreesasshownin**Table1**sothatMarsrotationislargelydecoupledfromthatoftheSun.MarsdoespresentlyhavetwosmallmoonsbuttheratioofthemassofMarstothatofthemoonsis53millionsothatthemotionorcaptureofthemoonsisnotexpectedtochangethemotionofMarsappreciably.ForcomparisontheratioofthemassofEarthcomparedtoEarth'smoonisabout83times.

## III. CONCLUSIONS

Bodies in the usniverse manifest a magnetosphere by two principal methods.The terrestrial planets are a separate group that may or not exhibit a magnetos-phere dependent on the details of the iron based core. Here it has been post-ulatedthataminimumaveragedensityof5350±50kg/m$^3$isrequiredforater-restrialplanettoexhibitastablemagnetosphere.Anironbasedcoreresultsfromthe fact that iron is the element with the maximum binding energy per nucleonthat can be made in the steady state of high mass stars. On this basis Mercurywouldhaveinitiallyexhibitedamagneticfieldwhichwasfrozenoutasthecorecooled. Earth, with a larger fraction of heavier elements and radioactive elementsacquiredinthehighlyenergeticeventthatcreatedtheEarth-Moonsystemhasastablemagnetospherethatisexpectedtolasttheprojectedlifetimeofthe Earth.The rotation rate of planets with highly conducting cores without a magneticfield for shielding is limited by the interaction with the changing dipolar mag-netic field of the Sun. Thus Mercury, once its own magnetic field is frozen out,andVenus,arelimitedtoslowrotationsbythechangingdipolarmagneticfieldof the Sun. Both the rotation axes of Mercury and Venus are within several de-greestothatoftheSunandsituatedformaximuminteraction.Marsontheoth-er hand has an axial rotation axis that is tilted about 25° from that of the SunandisdecoupledfromtheSun.TherelativelylowaveragedensityofMarsindi-cates that the core of Mars has limited conductivity that precludes interactionswiththeSun'schangingmagneticfields.

The other types of magnetospheres depend on high pressure and density hy-drogen. All gas giant planets as well as all stars exhibit magnetic fields which de-pend on convection currents that are not associated with core details or struc-tures.Ausefulsearchwouldbetofindagasgiantplanet,orastar,thatdoesnothaveamagneticfield.Theredoesnotseemtobeanyminimumaveragedensityrequiredforsuchobjectstoexhibitamagneticfield;theyallexhibitatomichy-drogen originated magnetic fields. The roughly half million year pole flippingperiod of the Earth indicates a magnetic field that is associated with the core oftheEarth.WhiletherapidpoleflippingtimeoftheSunofonlyabout11yearsatpresentindicatesthattheSun'smagneticfieldisnotassociatedwiththemassivecoreoftheSun.

Theenergybalanceequationand**Figure3**showthatthedistanceoftheterre-strialplanetfromtheSunplaysacrucialroleonthewaterstateonthesurfaceoftheplanet.Theplanetsurfacetemperaturemusthavebeenatleast273Ktohaveflowingliquidwater.Dissolvedsaltsmayacttoslightlylowerthisrequiredtem-perature.ForMarstohavehadflowingliquidwater,theenergybalanceequationrequires that a relatively high concentration of infrared absorbing gases musthave been present in the early Martian atmosphere. A value of at least about 4times the current Earth value must have been present before the Mars surfacedried.Dryingisfromthesurfaceandforarelativelystableandcoolcrustalotofwaterwouldhavebeenretainedinthecrust.Marsdoesnotexhibitplatetecton-ics so that there is little mixing of deeper crustal water with an original surfacecoating.

The terrestrial planets have iron based cores because iron has the highestbindingenergypernucleonthatcanbemadeinthesteadystatelivesofmassivestarsnomatterhowmassive.Theelementalabundancesofdifferentelementsinthe terrestrial planets are largely set by the shape of the binding energy pernucleon curve. This curve is set by fundamentally nuclear properties indepen-dentofanyparticularplanetorstar.Thissuggeststhatmanyoftheconclusionsreachedheremayalsobeapplicabletoexoplanets.

**ConflictsofInterest**

The authors declare no conflicts of interest regarding the publication of thispaper.

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