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Planets Around Pulsars in Globular Clusters

S. Sigurdsson,[1] I. H. Stairs,[2] K. Moody[3] Z. Arzoumanian,[4] and S. E. Thorsett[5]

[1] *525 Davey Laboratory, Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, Pa 16802, USA*

[2] *Dept. of Physics and Astronomy, University of British Columbia, 6224 Agricultural Rd., Vancouver, B.C., V6T 1Z1 Canada*

[3] *525 Davey Laboratory, Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, Pa 16802, USA*

[4] *CRESST and X-ray Astrophysics Laboratory, Code 662, NASA GSFC, Greenbelt, MD 20771, USA*

[5] *Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA*

Abstract. The first planet in a globular cluster was discovered orbiting the 11-millisecond pulsar/white-dwarf binary PSR B1620−26 in Messier 4. As more data have become available on this extraordinary object, the permitted range of parameters for this system has become increasingly tightly constrained, and the most recent data require an outer planet with mass of between 1 and 2 Jupiter masses in a hierarchical orbit, with orbital period of a few decades and with high orbital inclination relative to the plane of the inner pulsar/white-dwarf binary, yet relatively modest orbital eccentricity. The signatures of the Newtonian interaction between the planet and the white dwarf are clearly seen in the data. We discuss some of the implications of the current data, including constraints on scenarios for formation of the system and their implications. The data strongly favour a relatively recent exchange of the planet mass tertiary, and we may infer that the planet originally orbited a star which was a member of the cluster, at an orbital radius of a few AU, and that the planet is likely coeval with the cluster stars, having formed about 12.7 billion years ago.

1. Introduction

Radio pulsars are very stable, regularly rotating neutron stars (NS); the arrival of the radio pulses at Earth can be timed to sub-microsecond precision in the best cases. Radio pulsars are divided into two broad categories, regular young pulsars, with spin periods ranging from many tens of milliseconds to many seconds; and "millisecond pulsars" (MSPs), with spin periods ranging from less than 1.5 milliseconds, to some tens of milliseconds. The energy radiated by the pulsar (only a very small fraction of which is emitted at radio frequencies) is drawn from the rotational kinetic energy of the neutron star, which "spins down". The spin-down takes place over timescales ranging from thousands of years to hundreds of millions, or many billions, of years, depending on the type of pulsar, and is observed to be very predictable, ramping down the spin of the neutron star almost linearly for pulsars with long spin down timescales. Even with interruptions in observations, the pulse arrival times can be connected "phase coherently," linking together integer NS rotations over the course of years. As a result, future times of arrival (TOAs) can be predicted with high precision. The best timed pulsars, with short periods and sharp pulse profiles, have timing accuracy over long intervals that rivals the best laboratory timing standards. In particular, even small disturbances in TOAs can be observed and measured. Pulsar timing provides measurement of changes in velocity as well as position. The effective Δv measurable over intervals of years is less than mm/sec, some three orders of magnitudes better than achievable by other techniques (Lorimer and Kramer 2005).

The first confirmed extrasolar planets, the three terrestrial mass planets orbiting the millisecond pulsar PSR B1257+12, were discovered using pulsar timing (Wolszczan and Frail 1992; Wolszczan 1994).

1.1. Millisecond Pulsars in Globular Clusters

Globular clusters (GCs) represent a still largely underexplored set of targets for planetary searches. While there have been attempts to look for planetary transits in large GC data sets, these have been unsuccessful (Gilliland et al. 2000; Weldrake et al. 2007). In contrast, the indirect detection discussed here has already established the existence of planets in GCs, and such methods may be the best way forward in the medium term. A neutron star most likely forms originally in a type II supernova. Any planets orbiting the progenitor star when it exploded as a supernova are vanishingly unlikely to have survived the explosion, so most likely pulsars with planets acquire the planets after NS formation. It is possible that some NSs form from the direct collapse of massive white dwarfs forced over the Chandrasekhar mass limit by the accretion of additional matter, although the circumstances in which this leads to collapse rather than detonation as a type Ia supernova are not clear (Bailyn and Grindlay 1990; Ivanova et al. 2005).

A number of scenarios for planet formation around a neutron star, after the neutron star forms, have been proposed (Phinney and Hansen 1993). One scenario is that the supernova explosion had some residual material that was blown back or stalled in the explosion and fell back onto the neutron star, leading to a disk around the young neutron star. Intriguingly, infrared radiation has recently been observed around a young neutron star, 4U 0142+61, consistent with just such a "fallback disk" (Wang et al. 2006), and searches for planets around young pulsars continue (Posselt et al. 2006).

But the original planet pulsar, PSR B1257+12, is an old millisecond pulsar, not a young slowly spinning pulsar. The generally accepted picture (e.g., Bhattacharya and van den Heuvel 1991; Tauris and van den Heuvel 2006) is that millisecond pulsars form when NSs accrete gas in compact binary systems, probably so-called "low mass X-ray binaries". In these systems, a low mass star (solar mass or less) orbits close to a neutron star, transferring mass onto the neutron star, slowly spinning the neutron star up to millisecond periods over a time of tens of millions years. They are referred to as X-ray binaries, because the energy released during the accretion causes the system to glow brightly in the

X-rays. The vast majority of observed neutron stars are isolated, likely because it is difficult to arrange for a close low mass companion to be retained in an orbit around a neutron star when the progenitor star explodes as a supernova. Thus only a very small fraction of neutron stars in the galaxy go through an accretion phase, maybe one in ten thousand or so of neutron stars formed (Lorimer 2005).

The process of spin-up affords opportunities for planet formation. It is possible that during accretion some material flows outwards from the star, forming an "excretion disk", which moves outwards and cools, rather than accreting onto the neutron star (Banit et al. 1993). Such an excretion disk can provide an environment suitable for the formation of low mass planets in relatively close orbits, such as are seen around PSR B1257+12. This scenario requires that after spin-up, the pulsar ablates the core of its companion star, destroying it completely and leaving only the planets. We do see so-called "Black Widow" pulsars (e.g., Fruchter et al. 1988) that are in the process of ablating away the last remnants of their stellar companions, although it is not clear how often the ablation process will proceed to complete destruction of the star in general, in particular given the number of pulsars recently discovered in globular clusters with very low mass companions (e.g., Ransom et al. 2005).

An alternative version of this scenario short-cuts the accretion disk phase, by postulating that a small fraction of neutron stars physically impact their stellar companions, like old fashioned cannonballs. Supernova explosions can be asymmetric (e.g., Wang et al. 2006), and the newly formed NS can be kicked at high speed in random directions. The mechanisms by which the explosion becomes asymmetric are not fully understood. If the neutron star is kicked in just the right direction and impacts its companion, it may promptly shatter the star, and some of the debris may settle into a disk around the neutron star, serving both to spin up the neutron star to millisecond periods, and to provide a remnant disk from which planets may form in orbit around the newly formed millisecond pulsar (Phinney and Hansen 1993; Greaves and Holland 2000; Miller and Hamilton 2001; Lazio and Fischer 2004; Bryden et al. 2006; Currie and Hansen 2007).

The set of three planets orbiting PSR B1257+12 bears an interesting resemblance to a scaled down version of the inner Solar System, and understanding the process of planet formation around pulsars is likely to enhance substantially our understanding of planet formation in general, particularly for terrestrial planets. Currently the pulsar planets are the only example of terrestrial mass planets we have orbiting stars outside the Solar system.

Because of the large number of X-ray binary systems observed in GCs per unit mass (e.g., Pooley et al. 2003), GCs have long been expected to host correspondingly large populations of "recycled" or "spun-up" pulsars – MSPs. These neutron stars would have accreted matter and angular momentum during the X-ray binary phase (e.g., Alpar et al. 1982) and become active radio pulsars with millisecond spin periods. The first GC pulsar was discovered in Messier 28 about 20 years ago (Lyne et al. 1987), with the second discovery, an 11-msec pulsar in Messier 4, following soon after (Lyne et al. 1988). The discovery rate remained quite low for many years, however, until the availability of wide-bandwidth, high-resolution, fast-sampling spectrometers usable at high frequencies on large telescopes such as the 64-m Parkes and the 100-m Green Bank Telescope (GBT). By reducing the search impediments due to dispersive smearing and scattering in the interstellar medium, and by taking advantage of the enormous gain of these telescopes, current GC pulsar searches are much more sensitive, and are in fact turning up many interesting pulsars, some in exotic binary systems (e.g., Camilo et al. 2000; Ransom et al. 2005). Long-term timing observations, enumerating the pulsar rotations over the course of years, of these systems will have great power to detect or to set limits on the occurrence of planets around these pulsars (Blandford et al. 1987; Sigurdsson 1992).

1.2. The Power of Pulsar Timing

Pulsar timing aims to provide a fully descriptive and predictive ephemeris for a pulsar, incorporating spin period and derivatives, position and proper motion (and occasionally parallax) and any binary parameters that may be needed, using pulse times of arrival (TOAs) derived from cross-correlation of an observed profile with a standard template profile built up out of many hours of data on the pulsar. Many good descriptions of the timing procedure exist in the literature (e.g., Taylor and Weisberg 1989; Lorimer and Kramer 2005; Edwards et al. 2006). The exact counting of the pulsar spin cycles over billions of rotations ensures high precision in the parameter measurements in the long term, with good TOA measurement precision also playing an important role.

A lot of information can be gleaned from the set of measured spin frequency derivatives. A constant velocity offset Doppler-shifts the spin period of a pulsar, and is undetectable as the rest-frame spin period is not known. All pulsars exhibit a pronounced period first derivative, generally interpreted as due to the loss of rotational energy via magnetic dipole radiation but with possible contamination from the relative accelerations of the pulsar and the Solar System. These acceleration contributions may be many orders of magnitude larger than the intrinsic spin-down (Damour and Taylor 1991; Phinney 1992; Shklovskii 1970). A period second derivative usually indicates that the pulsar suffers from the stochastic rotational irregularities known as "timing noise." However, in a dense environment such as a cluster, or in the case of a long-period orbit, the gravitational acceleration can change over the timescale of the observations, and the jerk contributes to the second derivative, with higher derivatives of the acceleration appearing as higher spin derivatives. In particular, for observing intervals over a portion of a Keplerian orbit, these terms show up in the timing residuals as successively higher order polynomials in $(t - t_0)$ where t_0 is some fiducial orbital reference time within the interval (e.g., Joshi and Rasio 1997). As the observing interval becomes comparable to the orbital timescale the polynomial approximation breaks down and terms of all order contribute, or equivalently, the residuals are better represented by a trigonometric series with some characteristic orbital frequency. A broad introductory discussion on the sensitivity achievable can be found in Thorsett and Phillips (1992).

2. The M 4 Pulsar System

Precisely this sort of long-term monitoring led to a fundamental discovery about the nature of PSR B1620−26, the pulsar in M 4. It was quickly established after its initial discovery that the pulsar orbited a low-mass white dwarf companion every 191 days (McKenna and Lyne 1988). Subsequent observations over several years showed that the pulsar had an extremely large period second derivative (Backer et al. 1993; Thorsett et al. 1993), several orders of magnitude larger than would be expected from timing noise given the pulsar's period and spin-down rate (Arzoumanian et al. 1994). A jerk due to the cluster gravitational potential or a nearby star could also be dismissed as possibilities, and so it was suggested that the pulsar–white-dwarf binary was orbited by a roughly Jupiter-sized planet with a period of several tens of years (Backer et al. 1993; Thorsett et al. 1993; Phinney 1993).

Observations of PSR B1620−26 with the NRAO 140-foot, the VLA and the telescopes at Jodrell Bank have been thoroughly described in Thorsett et al. (1999). While we continue to incorporate new Jodrell Bank data (provided by collaborator A. Lyne) into the timing solution, the major North American monitoring of this pulsar is now (since 2001) accomplished using the 100-m NRAO Green Bank Telescope (GBT) in West Virginia and instrumentation with narrow frequency channels and fast sample rates. The great sensitivity of this telescope relative to the others results in far more precise TOA measurements in the modern era.

To determine the pulsar ephemeris, we use the standard TEMPO software package [1]. This accounts for the Earth's motion using the JPL DE405 Solar System ephemeris (Standish 1998). The full data set confirms that the period second derivative is large and that multiple period derivatives are required, going even beyond the 4 derivatives reported in Thorsett et al. (1999); see Fig. 1. Assuming that the observed derivatives represent the effects of an orbiting planet (see also Joshi and Rasio 1997) we can derive a Keplerian orbital solution for the outer binary, pointing to a planet of roughly one Jupiter mass with an orbit of about 50 years and an eccentricity around 0.15. One important point is that the simplest dual-Keplerian solution assumes that the entire observed period first derivative is produced by the planet. This is certainly not the case: besides an intrinsic component (which may well be small; Thorsett et al. 1993; Thorsett et al. 1999), the acceleration of the pulsar binary in the gravitational fields of the Galaxy and the cluster, along with its proper motion, will also contribute (Shklovskii 1970; Damour and Taylor 1991; Phinney 1992). This last set of kinematic corrections should affect the observed *orbital* period derivative in the same way, so if a change in orbital period is robustly detected and separated from planet-induced effects, it will be possible to adjust the Keplerian orbit to allow for the kinematic contribution to the pulse period derivative. However, the ambiguity between the intrinsic pulse period derivative and the outer orbit will remain until we have sampled a much larger fraction of the orbit than the $\sim$40% accessible up to this point.

Whether we fit a dual-Keplerian solution or multiple period derivatives, systematics are left behind in the timing residuals with clear periodicity at the 191-day orbital period of the inner binary; see Fig. 1. These variations may best be understood as perturbations of the inner orbit by the outer planet. Predictions of these perturbations were made in a stationary-planet approximation by Rasio (1994) and Joshi and Rasio (1997): specifically, for the inner binary, the orbital eccentricity, e, the longitude of periastron, ω, and the or-

[1] http://www.atnf.csiro.au/research/pulsar/tempo

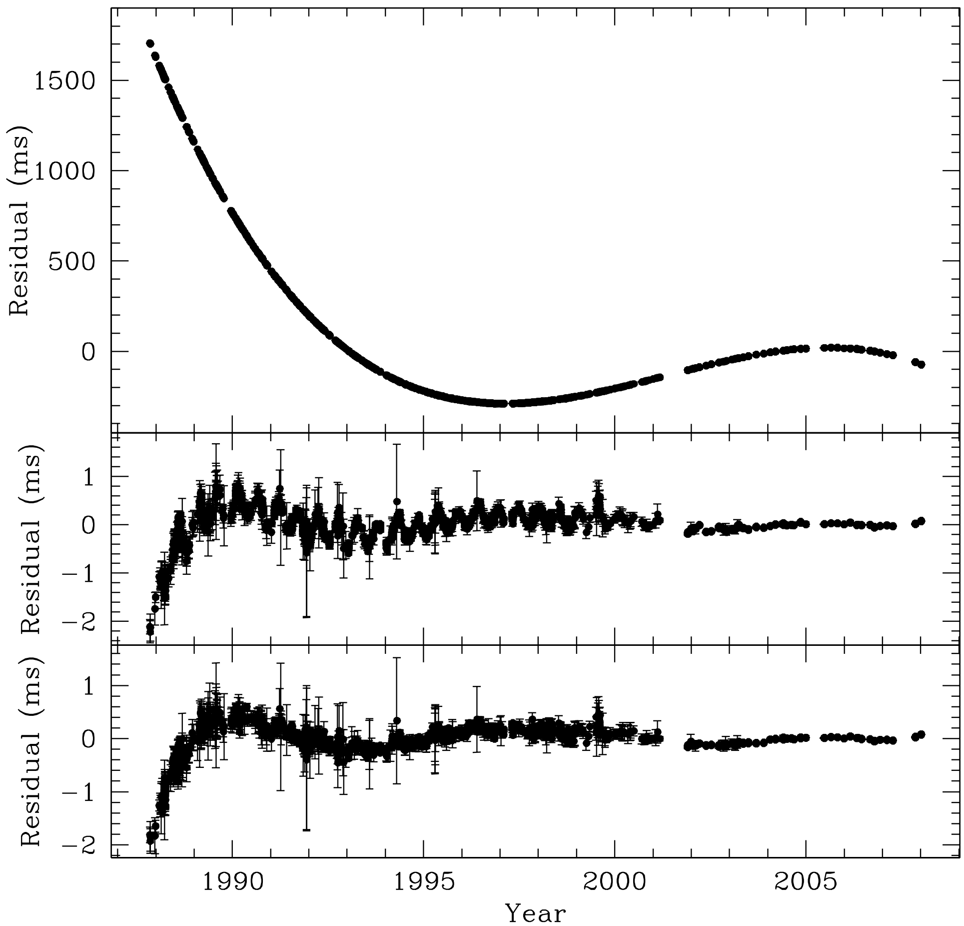

Figure 1. Timing residuals for PSR B1620−26 using data from the NRAO 140-foot, the VLA, Jodrell Bank and the GBT. Top panel: residuals relative to a timing model including only astrometric parameters, the inner binary orbit (all held fixed), frequency and a single frequency derivative. Middle panel: residuals relative to a model incorporating two Keplerian orbits but no perturbations of the inner orbit; large systematics are evident at the 191-day period of the inner orbit. Bottom panel: residuals relative to a model incorporating two Keplerian orbits as well as multiple long-term perturbations to the inner orbit due to the outer planet. Some systematics are still visible in the timing solution.

bital inclination, i, relative to the line of sight, are expected to change with time. The predicted change in e is especially interesting, as the observed orbital eccentricity of 0.025 is orders of magnitude larger than predicted or observed in "normal" millisecond-pulsar–white-dwarf binaries that have undergone tidal circularization (Bhattacharya and van den Heuvel 1991; Phinney 1992). However, the production of the actual observed e given the timing-derived planetary parameters is a more complicated question and will be discussed further below.

The largest observed perturbative effect is a secular decrease in the projected semi-major axis, $x = a \sin i$, of the inner orbit, first reported in Arzoumanian et al. (1996), Thorsett and Arzoumanian (1999), and Thorsett et al. (1999) and now measured to far higher precision. This is most likely not due to a change of the semi-major axis a but instead corresponds to the plane of the orbit precessing away from our line of sight. Thorsett et al. (1999) used the measured $\dot{x}$ together with the equations and Monte Carlo method from Joshi and Rasio (1997) to derive probability density functions for the planet's mass, orbital period and orbital semi-major axis, along with the inclinations of the two orbits. With the inclination angle probability distribution function measured for the inner orbit, and the assumption of a $1.35\,M_{\odot}$ pulsar (Thorsett and Chakrabarty 1999), the mass of the pulsar's white dwarf companion can be predicted. In fact, a mass consistent with this prediction can be inferred for the coincident white dwarf through cooling models (Sigurdsson et al. 2003). This companion white dwarf turns out to be low-mass compared to the other white dwarfs in the M 4 cluster, and young, in agreement with a scenario in which it recently spun up the pulsar (Sigurdsson et al. 2003, and see below).

With the longer radio data span, there is increasing evidence for additional perturbations, namely possible changes in ω and the orbital period $P_{\rm b}$, though as noted above the latter variation may have multiple contributions. While the inclusion of these derivative parameters improves the fit to the data, the overall reduced-χ^2 of the dual-Keplerian timing fit is quite large, and it is clear that we have not yet correctly accounted for all the systematics in the timing residuals (Fig. 1). Efforts to improve the fits are proceeding in parallel with development of code to model the secular changes produced by the moving planetary companion.

3. Modeling PSR B1620−26

There are two aspects to modeling PSR B1620−26: one is the formation of the system and its long term dynamical history in the cluster; the second is fitting the current dynamical state of the system to the observed parameters and constraining the possible formation scenarios from the current state.

Various formation scenarios for this system have been proposed. There are several ways in which the current system could have been produced with an old planet and exchanges among stars. One scenario suggests that the main sequence star around which the planet formed interacted with a binary containing the neutron star and a hypothetical third object (Sigurdsson 1993; Sigurdsson 1995). The neutron star exchanged to become a member of a binary with the first star, ejecting the third star. The first star then evolved into a red giant, spinning up the NS and also circularizing the binary's orbit, leaving the millisecond pulsar-low mass white dwarf binary we see today with the planet in a wide orbit. In another somewhat different exchange scenario, the binary already consisting of the current pulsar and inner companion exchanged the planetary companion from a passing field star (Ford et al. 2000a; Fregeau et al. 2006). In both the scenarios above the planetary companion formed independently in orbit around a cluster main sequence star and was exchanged into the current system, the primary difference between the scenarios being whether the planet was exchanged concurrently with the star that evolved to become the white dwarf currently observed in the system, or whether it exchanged into the system in a separate encounter. A significantly different formation scenario suggested in (Beer et al. 2004) is that the planet was formed from a disk surrounding the common envelope of the binary by collapse through a gravitational instability, possibly triggered by a passing star. Yet another scenario postulates that the pulsar might have formed through accretion induced collapse of a massive white dwarf, with the planet formed in a metal rich accretion disk (Livio et al. 1992). These different scenarios for the formation of the triple system, whether exchange, gravitational collapse or disk formation, have different consequences for the dynamics of the outer body, particularly by determining the probable initial eccentricity and inclination of its orbit. While the planet formed in an excretion disk, or by a star passing through the disk around a common envelope might be constrained to a low inclination orbit, an exchange scenario would have no constraint on the inclination of the orbit; perpendicular orbits would be just as probable as nearly co-planar ones, and even retrograde orbits would be possible. Constraints on the elements of the outer orbit can help distinguish among the possible histories of this interesting system.

3.1. Kozai Pumping

The Kozai mechanism operates for hierarchical triples in which the outer body is inclined above some critical large inclination angle to the plane of the inner binary (Kozai 1962). The resulting dynamics conserve a third integral of motion, a combination of the inclination of the outer body, i_2, and the eccentricity of the inner binary, e, allowing for exchange of the z-component of the angular momentum between the different parts of the system. We use octupole level three-body secular perturbation equations to examine the evolution of the eccentricity of the orbit of the low mass white dwarf around the pulsar in the PSR B1620−26 system by varying several parameters around suspected values, following Ford et al (2000). Taking into account general relativistic precession of the periastron of the inner binary, and using the recent estimated values for the sizes and eccentricities of the orbits, we find that for orbits with high relative inclination, i.e., $82 < i_2 < 95$ degrees for a mass for the third body of about 2 Jupiter masses, the eccentricity of the inner orbit can be made as high as the observed value ($e = 0.025$), with a change in inclination of about half a degree during the oscillation from low to high eccentricity for the white dwarf orbit. This result constrains possible formation scenarios for this system, although a definitive answer will depend on separating the degeneracy for the spin period first time derivative, and a tight constraint on the relative inclination of the orbits.

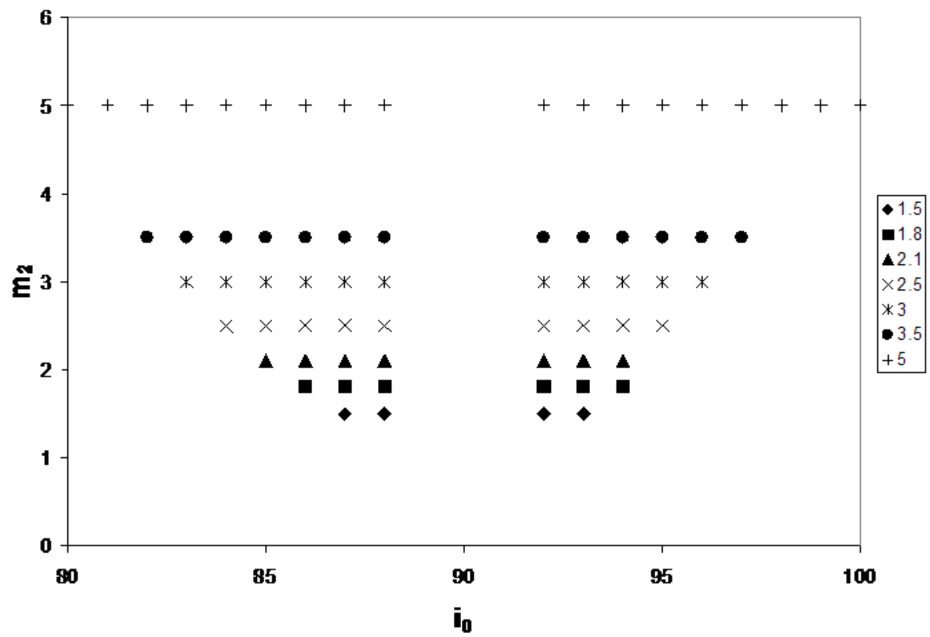

Figure 2. Plot of initial conditions for different planetary masses and initial inclinations, $i_0 = i_2(t = 0)$, which have $e_{max} > 0.025$, for the near orthogonal family of solutions. Symbols indicate particular values of the planetary mass in units of Jupiter masses, as indicated in the legend. For inclinations greater than about 86 degrees, the white dwarf eccentricity is consistent with second order Kozai pumping and planetary masses less than 2 Jupiter masses. From Moody & Sigurdsson (in preparation).

We solve the octupole secular evolution equations (29)-(32) from (Ford et al. 2000b) with the sign change to the constant C_3 as indicated in (Blaes et al. 2002) using a 4th order Runge-Kutta integrator. General relativistic precession of the inner binary was included in the rate at which the orientation of the inner orbit changes. The inner binary is assumed to have masses of 1.4 and 0.3 $M_\odot$ in an orbit of period 191 days and *initial* eccentricity of 0.0001. The outer body is set in an orbit of 13.74 AU (P2=39.2 years), which was the best fit orbital period with the data available through 2006. The eccentricity of the outer orbit (e_2), mass of the third body (m_2), and inclination of the orbit with respect to the inner binary (i) make up the parameters to be explored. Varying e_2 from 0.05 to 0.5 increases maximum e and shortens the period of variation in $e(t)$; for the low inclination regime a high $e_2(0)$ can get to the observed e where a lower $e_2(0)$ doesn't. We also performed a few runs with a pular mass of 1.25 $M_\odot$ to examine the effect of the inner binar mass ratio. The lower primary mass increases the difference in maximum e between $e_2(0)$ of 0.05 and 0.5, but at about $e_2(0) = 0.2$ they are the same.

We find that for inclinations within 5 degrees of perpendicular, and masses of the outer planet above 2 times Jupiter's mass, the eccentricity of the

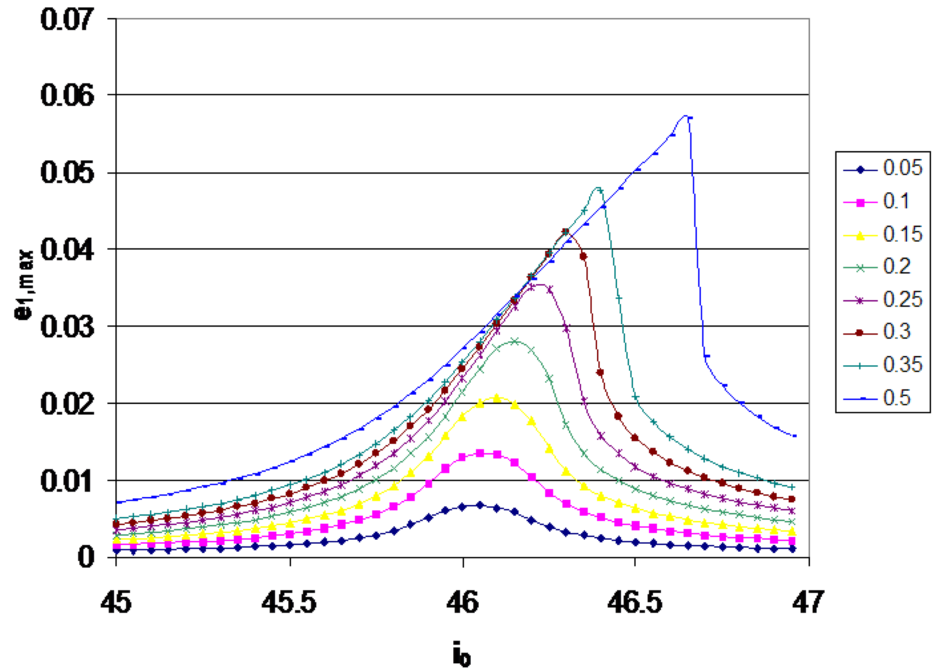

Figure 3. The value of the initial planetary inclination at which e_{max} is maximum, for the low inclination regime for different values of the eccentricity of the planetary orbit, e_2. For higher values of $e_2(0)$, the Kozai resonance dominates and pushes the inclination for which the eccentricity is maximized to higher values, whereas at low $e_2(0)$ the eccentricity is driven more by the combination of Kozai and relativistic precession. Maximum e at particular planetary masses are achieved when the Kozai effect is in resonance with the relativistic precession. From Moody & Sigurdsson (in preparation).

PSR B1620−26 binary can be made as large as observed. A reasonably firm lower limit of $1.5M_{Jup}$ for these inclinations can be set within the range of orbital parameters and masses explored in these simulations. The current inclination is 0.4 degrees less than that of the initial inclination. For moderately inclined orbits, the eccentricity has a local maximum for i of 46 and 133 degrees, but only produces the observed e at the octupole level of approximation for planetary masses greater than 3 Jupiter masses or values of $e_2 > 0.3$. The high inclinations necessary to explain the eccentric inner binary indicate that a formation scenario involving exchange is needed.

4. Conclusion

The currently observed parameters for PSR B1620−26 are best fit by a hierarchical triple system, consisting of a primary millisecond pulsar orbited by a low mass white dwarf. Orbiting the center of mass of this inner system is a low mass object, possibly less massive than 2 Jupiter masses, on a highly inclined, moderate eccentricity orbit with an orbital period of few decades. The last twenty years of observations have seen the tertiary in this system cross the plane of the sky, and the resulting sign change in the spin period derivatives produces an unambiguous confirmation that the timing residuals are due to newtonian orbital dynamics. There is currently a residual degeneracy in some of the timing parameters, so not all the orbital parameters are equally well determined, a full solution will required a time explicit three body model for the system, rather than the quasi-static coupled Keplerian solutions used to date. Initial exploration of the full solution space indicates the orbital solution is consistent with this description.

The high inclination and relatively low eccentricity of the tertiary are most consistent with exchange scenarios for the formation of the system, suggesting the planetary object formed around a main sequence star in the cluster, possibly at the time the cluster stars formed. The cooling age of the white dwarf and the position of the system in the cluster suggest a single exchange scenario (Sigurdsson 1993; Sigurdsson et al. 2003), although the double exchange scenario can also be consistent with the data (Fregeau et al. 2006).

There is a correlation between stellar metallicity and the probability of a "hot Jupiter" orbiting the star, that is observed for stars in the disk of the Milky Way near the Sun (Fischer and Valenti 2005). Given these observations of the local field population, the hints at a population of long period jovians orbiting low metallicity stars, that may be inferred from observations of pulsars in globular clusters, is particularly intriguing. With the current small sample, the data may be due to unique circumstances, such as a one-off formation method (Livio et al. 1992; Beer et al. 2004), or, we may be seeing a distinction between formation and migration dynamics in different systems, or, we may be seeing evidence for two distinct modes of planet formation (Boss 2002). The absence of "hot Jupiters" in globular clusters monitored for transits to date (Gilliland et al. 2000; Weldrake et al. 2007), is puzzling given the existence of PSR B1620−26's companion. More data on long orbital period jovians in low metallicity stellar systems would be of interest.

Clearly, the sort of mechanisms by which the planets around PSR B1257+12 formed might also operate for the pulsars formed in globular clusters. However, due to the high density of stars, there is a potential problem of survival for any planets, the occasional close passage of another star might disrupt the orbits of such planets on long time scales, leading to disruption, orbit crossing, collisions and eventual ejection (Sigurdsson 1992). But, such passages can also serve to increase the odds of detecting planets around pulsars. *If* stars in globular clusters have planets around them, then during close passages planets may occasionally be *exchanged*, from their orbits around their parent star, to an orbit around a pulsar. A planet orbiting the typical solar like star in a globular cluster is very hard to detect, although attempts have been made to do so (Gilliland et al. 2000), but a planet orbiting a millisecond pulsar in a globular cluster is comparatively easy to detect. The orbits of exchanged planets are in general qualitatively different from the orbits of planets formed *in situ* around the pulsar, such as for PSR B1257+12. The latter are in close circular near coplanar orbits, and the planets are relatively low mass; in contrast exchanges tend to slightly favour the most massive planets, and will lead to wide, eccentric orbits.

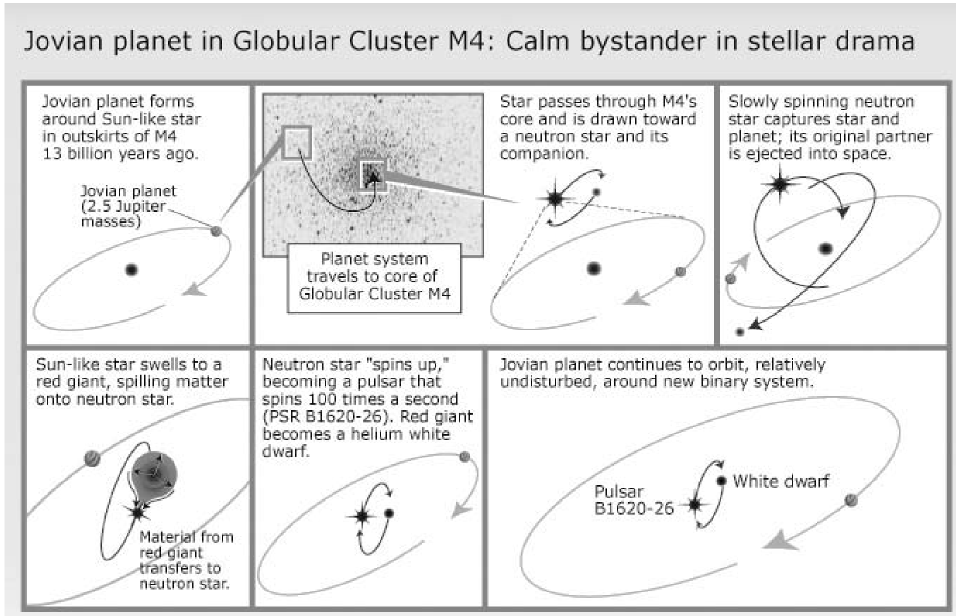

Figure 4. A schematic illustrating one of the proposed exchange formation mechanisms for the planet around PSR B1620−26 in the globular cluster Messier 4. In this figure the pulsar is assumed to have formed in an intermediate mass binary with a moderately massive white dwarf companion, some 12-13 billion years ago. More recently, maybe some 1-2 billion years ago the original massive white dwarf was ejected by an encounter in the core of the cluster with a main sequence star near the turnoff mass (and somewhat more massive than the original white dwarf). The current planetary companion is assumed to have been bound to this main sequence star and to have exchanged into the pulsar system with the star. The associated dynamical recoil ejects the pulsar system from the core of the cluster onto a wide radial orbit which takes a couple of billion years to shrink back towards the core through dynamical friction. The main sequence star then evolves on to the giant branch, but core evolution is terminated by contact and mass transfer with the pulsar, which is also recycled into the current millisecond pulsar through an x-ray binary phase. This is estimated to have occurred a few hundred million years ago at which point the current, young, low mass white dwarf companion formed and the stellar envelope was ejected, leaving the system in its current state. (Adopted from a Space Telescope Science Institute/NASA press image, http://hubblesite.org/newscenter/archive/releases/2003/2003/19/ and see also (Sigurdsson 1993; Sigurdsson et al. 2003)).

Future observations of additional pulsar planets, whether in globular clusters or in the field would be very useful.

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