Exoplanets whose orbit is misaligned with the spin of their host star could have originated from high-speed gas blobs, which are observed in multitudes in nearby supernova remnants and planetary nebulae. These blobs grow in mass and slow down in the interstellar medium (ISM) by mass accretion and cool by radiation. If their mass exceeds the Jeans mass, they collapse into hot giant gas planets. Most of the 'missing baryons' in galaxies could have been swept into such free-floating objects, which could perturb stellar planetary systems, kick bound planets into misaligned orbits or be captured themselves into misaligned orbits. The uncollapsed blobs can then collapse or be tidally disrupted into a tilted gas disk where formation of misaligned planets can take place. Giant Jupiters free floating in the Galactic ISM may be detected by their microlensing effects or by deep photometry if they are hot.

Subject headings: planetary systems-planets and satellites: formation

1. Introduction

The prevailing theories of planet formation posit that planets are formed in the disk of gas and dust encircling a young star (Kuiper 1951; Montmerle et al. 2006). A close alignment between the rotation axis (spin) of the star and that of the orbital motion of the planets is expected because a star and its planets inherit their angular momentum from a common source - the protostellar disk. However, measurements of the relative spin orbit alignment of transiting extrasolar planets (exoplanets) through the Rossiter-McLaughlin effect (Rossiter 1924; McLaughlin 1924) reveal that a considerable fraction of the hot Jupiters (exoplanets with a mass similar or greater than that of Jupiter and much hotter) have misaligned spin-orbit (Hebrard et al. 2008; Winn et al. 2009a; Johnson et al. 2009; Winn et al. 2009b; Pont et al. 2009, 2010; Narita et al. 2009, 2010; Winn et al. 2010; Schlaufman 2010; Hirano et al. 2010; Triaud et al. 2010; Hebrard et al. 2011; Simpson et al. 2011). Other
properties of hot Jupiters, such as a temperature independent of their distance from their host star and of its temperature as observed for the hot Jupiters orbiting the nearby star HR 8799 (Marois et al. 2010), also challenge (Close 2010) the \textit{in situ} planet formation theories (Mizuno 1980; Nero & Bjorkman 2009).

Native planets formed in the protostellar disk may be scattered later into misaligned orbits by planetary encounters (Chatterjee et al. 2008; Ford & Rasio 2008) or by the Kozai mechanism (Malberg et al. 2007; Fabrycky & Tremaine 2007). But, such mechanisms are unlikely to explain the large fraction of hot Jupiters with misaligned orbits (Hebrard et al. 2011) and a temperature not correlated with their distance from the host star (Marois et al. 2010). Here we suggest an alternative plausible \textit{ex situ} origin of hot giant gas planets with misaligned spin-orbit, namely, the formation of high-speed gas blobs in the explosive death of stars. Such gas blobs are observed in large numbers in nearby supernova remnants (Fesen et al. 2006, 2007) planetary nebulae (O’Dell et al. 2002; Matsuura et al. 2009) and star formation regions. The existence of these gas blobs with cometary-like appearance (see Figs.1,2), probably due to overtaking winds, was not expected, their origin is still not understood and their fate is unknown. We shall argue that they grow in mass and slow down in the interstellar medium (ISM) by sweeping in the ambient matter in their way. They cool by radiation and if their mass exceeds the Jeans mass (Jeans 1902) they contract gravitationally into giant Jupiters. The collapsed and uncollapsed Jupiter-mass objects can perturb stellar planetary systems and kick bound planets into misaligned orbits. They can also be captured into misaligned orbits around host stars. The uncollapsed ones may then collapse or be tidally disrupted and form a tilted gas disk where \textit{in situ} formation of planets with misaligned spin-orbit can take place.

If the numbers and properties of the cometary blobs (CBs) observed in the supernova remnant Cassiopeia A (Cas A) and in the Helix nebula represent faithfully those formed in other supernova remnants (SNRs) and planetary nebulae (PNs), then the total number of Jupiter-mass objects free-floating in the ISM of our Galaxy may exceed the number of stars by more than two orders of magnitude. These free-floating Jupiter-mass objects could have accreted most of the gas and dust in the ISM of galaxies and may explain the presently small mass ratio between gas and stars in galaxies (∼ 1:10 in the Milky Way).

The fraction of CBs that end up as free-floating Jupiters in the Galaxy cannot be reliably estimated from theory. However, the density of free-floating Jupiters in the Galaxy can be measured through their microlensing effects. In fact, presence of a significant fraction of the ‘missing baryons’ in galaxies in free-floating Jupiters is consistent with the measured optical depth for microlensing towards the Galactic bulge by the MACHO (Alcock et al. 2000a) and OGLE (Sumi et al. 2006) collaborations (see section 5). The MACHO collaboration also
reported an optical depth towards the stars in the Large Magellanic Cloud (LMC) which is larger than those expected from lensing by the known populations of stars in the Galaxy and the LMC (Alcock et al. 2000b; Bennett 2005). However, the microlensing optical depths towards the LMC stars that were measured by the EROS (Tisserand et al. 2007) and OGLE (Wyrzykowski et al. 2010) collaborations, are much smaller than that measured by MACHO and are consistent, within errors, with those expected from the known stellar populations in the LMC and the Galaxy. In view of the conflicting results, the small statistics of lensing events, and the large uncertainties in the modeling of the LMC, it is difficult to draw a definite conclusion on free-floating planets in the LMC from the measured values of the microlensing optical depths of the LMC. Second generation microlensing surveys using ground based telescopes, or space based telescopes such as The Wide-Field Infrared Survey Telescope (WFIRST), that unlike Kepler, will be sensitive also to free-floating planets (Bennett et al. 2011; Catanzarite 2011) and will measure or set limits on their density in the ISM, their masses and the fraction of baryons in the Galaxy which reside in such planets.

Observational support for the hypothesis of \textit{ex situ} origin of misaligned hot Jupiters and other planets in orbits around host stars could also come from the detection of a large population of free-floating hot Jupiters in the ISM in deep pencil searches with extremely large optical and infra-red telescopes (ELTs) equipped with advanced adaptive optics and having a much greater light collecting ability than that of the current largest telescopes. A large population of free-floating hot Jupiters in the ISM may also contribute significantly to the unresolved diffuse infra-red background radiation.

Finally, dramatic flux changes occurring over several weeks to months in the radio flux from quasars, such as 0954+658 (Fiedler et al. 1987), and episodes of multiple images of radio pulsars (Cordes and Wolszczan 1986; Rickett 1990) were shown (Walker and Wardle 2010) to be reproducible by refraction from the ionized skin of an hypothesized large population of neutral clouds having a few astronomical units in radius and masses \(\lesssim 10^{-3} M_{\odot}\), which are free floating in the Galactic ISM and are exposed to the Galactic ionizing UV flux.

2. Cometary Blobs in SNRs and PNs

High resolution imaging of nearby young supernova remnants from the explosive death of massive stars, such as SNR Cass A (Fesen et al. 2006) and SNR 3C 58 (Fesen et al. 2007) and of nearby planetary nebula remnants of the explosive death of sun-like stars, such as the Helix nebula (Matsuura et al. 2007, 2009), the Ring nebula, the Dumbbell nebula and the Eskimo nebula, reveal that thousands of cometary blobs (CBs) with masses similar to that of Earth and radii of hundreds of astronomical unit are moving away from the center of the
explosion along radial directions. The fate of CBs formed in the explosive deaths of stars is not known. Probably, most of these CBs grow in mass and slow down by accreting the ISM particles (gas and dust) in their path, and cool by radiation. When their mass exceeds the Jeans mass \( M_J = 3 k T R/4 G m_p \), where \( k \) is the Boltzman constant, \( T \) is the temperature of the \( H_2 \), \( R \) is the radius of the CB and \( m_p \) is the proton mass, they collapse gravitationally into a hot Jupiter.

The outer 1825 CBs observed in the SNR Cass A (Fesen et al. 2006) have typical velocities \( V_0 \approx 10,000 \) km/s, a radius \( R \approx 0.1'' \) corresponding to 0.002 pc (at 3.4 kpc, the estimated distance to Cas A), and \( n_b \geq n_e = 0.7 \times 10^4 \) cm\(^{-3} \), i.e., a mean column density \( N_{CB} \sim 6 \times 10^{19} \) cm\(^{-2} \), and a mass \( \geq 1.2 \times 10^{28} \) g (~twice that of Earth).

The measured radial velocities of over 450 CBs in SNR 3C 58, reveal (Fesen et al. 2007) two distinct populations, one with average projected velocities of 770 km/s, and a high NII/H\(_\alpha\) line emission ratio and the other showing velocities less than 250 km/s and a much lower NII/H\(_\alpha\) line emission ratio. It was suggested that the low velocity populations were formed in the ejecta of the progenitor star long before its supernova explosion while the higher velocity CBs were formed during or after the SN explosion.

The estimated current rate of Galactic core collapse SN explosions (Tammann et al. 1994) is \( \sim 1/50 \) y. This rate, being proportional to the Galactic star formation rate, was much higher in the past. Thus, over the past 13.2 Gy or so, the estimated age of the oldest stars in the Galaxy (Ferbel et al. 2007), there have been more than \( 2.6 \times 10^8 \) core collapse SN explosions. If the mean number of CBs formed in an SN explosion is represented by the 1825 CBs resolved in the SNR Cas A, then more than \( 10^{12} \) CBs were launched into the ISM of the Galaxy in SN explosions during its age.

Many more CBs are launched in planetary nebulae than in SN explosions. Detailed observations of the nearby Helix nebula at a distance of 219 pc with high resolutions telescopes such as the Hubble Space Telescope (HST), the Very Large Telescope (VLT) and the Subaru telescope revealed more than 40,000 CBs (Matsuura et al. 2009). If these CBs are well represented by the CB KI, which was studied in detail in Matsuura et al. 2007, then their typical radius is 0.75 arcsec or \( R=0.0008 \) pc and their \( H_2 \) density is \( 8 \times 10^4 \) cm\(^{-3} \). These yield a CB mass \( 1.7 \times 10^{28} \) g, which is three times larger than the mass of Earth, \( (5.98 \times 10^{27} \) g) and a mean column density \( N \sim 2 \times 10^{20} \) cm\(^{-2} \).

The local space density of white dwarf stars, presumably mostly born in PNs, was found to be (Holberg et al. 2002) \( \sim 5.0 \times 10^{-3} \) pc\(^{-3} \), with a corresponding mass density of \( \sim 3.4 \times 10^{-3} M_\odot \) pc\(^{-3} \), which is roughly 5\% of the local mass density in stars that was measured (Creze et al. 1998) with Hipparcos (\( \sim 7.6 \times 10^{-2} M_\odot \) pc\(^{-3} \) corresponding to a local
number density \( n_s \sim 0.23 \text{ pc}^{-3} \). The birth rate of planetary nebulae is roughly that of white dwarfs. Assuming that the number of CBs per planetary nebula is \( \sim 40,000 \) as was observed in the Helix Nebula with the Spitzer space telescope and the Subaru telescope (see Fig.1) and that the local ratio of white dwarfs to stars represents the Galactic ratio, then the local density of Jupiter-mass objects is roughly \( n_J \sim 200 \text{ pc}^{-3} \) and their number in the Galaxy exceeds the number of stars by roughly three orders of magnitude.

3. The fate of high speed CBs

High-speed projectiles such as those ejected in SN explosions and launched by micro-quasars decelerate in the ISM by accreting the gas and dust on their way. Momentum conservation with the neglect of radiative losses seems to describe well their deceleration: Consider first the deceleration of the spherical shell of initial mass, radius and radial velocity, \( M_0, R_0, V_0 \), respectively, ejected in SN explosion into an ISM of a constant density \( n_{ism} \). Momentum conservation with the neglect of energy losses yields a radial velocity

\[
V = \frac{V_0}{1 + \Delta M/M_0},
\]

where as a function of swept in ISM mass \( \Delta M = 4\pi n_{ism} m_p (R^3 - R_0^3)/3 \). In the limit \( R \gg R_0 \), the age as a function of the radius of the expanding shell has the form

\[
t = \frac{R}{V_0} \left[ 1 + \frac{\pi R^3 n_{ism} m_p}{3 M_0} \right].
\]  

(1)

Eq. (1) describes well the transition from a linear expansion of the entire SN shell, \( R \approx R_0 + V_0 t \), observed, e.g. in SN1987A and SN1993J at early times to the asymptotic behaviour, \( R \approx [3 M_0 V_0 t/\pi n_{ism} m_p]^{1/4} \) for swept in mass \( \Delta M \approx 4 \pi n_{ism} m_p R^3/3 \gg M_0/4 \).

The slow-down of a CB of initial mass \( M_0 \), radius \( R \), baryon density \( n_b \) and velocity \( V_0 \) by mass accretion along its path in the ISM is described by \( M \, dV = -V \, dM \), i.e.,

\[
\frac{M_0 V_0}{V} \, dV = -V^2 \pi R^2 n_{ism} m_p \, dt.
\]  

(2)

In order to reduce its velocity by a factor \( k \), a CB must accrete an ISM mass \( \Delta M = (k-1) M_0 \). Neglecting its relatively slow thermal expansion, it must sweep in a column density \( k-1 \) times its own mean column density \( N_{CB} = 4 n_b R/3 \). i.e., cross a distance \( d = (k-1) (4 n_b R/3 n_{ism}) \) which takes a time \( t_d = (2 n_b R/3 n_{ism} V_0) (k^2 - 1) \).

Initially, the temperature of the surface of a CB facing the young neutron star (ns) in SNRs or the white dwarf (WD) in PNs is determined by its illumination by the young neutron star at the center of the SNR or the white dwarf at the center of the PN. For instance, in the absence of an internal or an external heat source other than the light of the white dwarf at the center of the PN at a distance \( D \sim 0.8 \text{ pc} \), their surface temperature \( T_{CB} \)
of their illuminated side would be roughly, \( T_{CB} < T_{WD} \sqrt{R_{WD}/2^{1/2} D} \sim 0.42\text{K} \) for a typical WD radius \( R_{WD} \sim 7000\text{ km} \) and WD surface temperature \( T_{WD} \sim 30,000\text{K} \). The illuminated surface, however, is visible from Earth at such distances by light emitted from the decay of atomic and molecular levels which are excited by the incident light. A thin photoionized "skin" of the CBs can be maintained by the Galactic UV background radiation even at large distances from their source. This photoionized skin of CBs in the ISM can be responsible for strong scintillations observed in the radio emission from extragalactic and Galactic compact radio sources [Walker and Wardle (2010)].

Far away from the central star, the only significant heat source of CBs is the kinetic energy deposited by the collision of the swept in ISM gas and dust particles with the CBs’ molecular gas. Without any other heat source, the CBs cool by radiative decay of rotational and vibrational molecular levels excited by internal collisions. The temperature of a CB adjusts itself such that its cooling rate by radiation equals the rate of this energy deposition. If the radiation can be approximated by a black body radiation, then

\[
4 \pi R^2 \sigma T^4 = \frac{n_{ism} m_p V^3}{2} \pi R^2.
\]

This yields a rather low equilibrium temperature

\[
T = \left[ \frac{n_{ism} m_p V^3}{8 \pi} \right]^{1/4} \approx 0.044 \left( \frac{V}{\text{km}} \right)^{3/4} \left[ \frac{n_{ism}}{\text{cm}^3} \right]^{1/4} \text{K},
\]

where \( \sigma \) is the Stefan-Boltzman constant. This equilibrium temperature decreases when the CB decelerates by mass accretion from \( \sim 44\text{K} \) for \( V = 10,000\text{ km s}^{-1} \), to below 10K for \( V < 1400\text{ km s}^{-1} \).

Because of their low temperature and their large size, thermal expansion of CBs is negligible during their deceleration: Consider a non collapsed spherical blob of \( H_2 \) gas of a total mass \( M \), a constant density and an initial radius \( R_0 = 10^{15} \text{ cm} \) that expands with the speed of sound \( \dot{R} = c_s = \sqrt{\gamma k T/2 m_p} \), where \( \gamma = 1.4 \) is the adiabatic constant for an ideal \( H_2 \) gas. If the CB cools mainly by radiation according to the Stefan Boltzmann law, then \( (3/2) (M/2 m_p) k \dot{T} = -4 \pi R^2 \sigma T^4 \). By dividing these two rates, separating the \( R \) and \( T \) dependences and integrating the resulting equation from initial \( T_0 \) to a final \( T \ll T_0 \), we obtain

\[
\frac{R - R_0}{R_0} \approx R_0^3 \sqrt{\frac{\gamma k T}{2 m_p}} \frac{3 M}{40 m_p} \frac{k T}{4 \pi \sigma T^4} \left( \frac{R - R_0}{R_0} \right),
\]

where we have assumed that \( (R-R_0) \ll R_0 \). Indeed, for \( M < 0.01 M_\odot \) and \( T \sim 10\text{K} \), the RHS of the last equation yields a negligible expansion, \( (R-R_0)/R_0 \approx 0.0035 \).
The outer CBs observed in the SNR Cas A (Fesen et al. 2006) have typically a mean column density $N_{CB} \geq 6 \times 10^{19}$ cm$^{-2}$, and a mass $\sim 1.2 \times 10^{28}$ g ($\sim$ twice that of Earth). Hence Galactic column densities above a few $10^{21}$ cm$^{-2}$ are sufficient to slow down the CBs from Cas A to velocities smaller than the local Galactic escape velocity (Smith et al. 2007) $V_{esc} \sim 550$ km/s. Such slowed-down CBs continue to accrete interstellar matter, grow up in mass, slow down further and cool by radiation until they are captured by a host star or their mass exceeds the Jeans mass, $\sim 0.01 M_\odot$ for $T \sim 10^4$K and $R \sim 10^{15}$ cm, and they collapse to hot Jupiters free-floating in the Galactic ISM. Moreover, most star formation and SN explosions take place within large molecular clouds. This is a natural consequence of their low temperatures and high densities. Large molecular clouds have a typical size of tens of pc and a typical baryon density $n_b \sim 10^3$ cm$^{-3}$. Most of the CBs which are ejected in a supernova explosion within such a dense environment slow down completely within the molecular cloud. Some may escape into the ISM with rather a small velocity and virialize there. Some of the CBs in the molecular clouds can seed there star formation by mass accretion, while other CBs can be captured there into planetary orbits around newly born stars. Very high velocity CBs from SN explosions outside molecular clouds that are moving in Galactic directions of small column density will escape into the low-density intergalactic space where they will expand before they reach the Jeans mass and enrich the intergalactic medium (IGM) with metals produced in SN explosions.

In the case of SNR 3C 58, the measured radial velocities of the CBs are smaller than those observed in Cas A, roughly by an order of magnitude, probably because of their deceleration during the long time since the SN explosion (about 3000-4000 years ago) relative to that of Cas A (about 330 years ago).

The fate of the CBs observed in planetary nebulae probably is similar. If they are well represented by CB K1 in the Helix nebula at a distance of 219 pc that has been studied in detail (Matsuura et al. 2007, 2009), they have a typical CB mass of $1.7 \times 10^{28}$ g, which is three times larger than the mass of Earth, and a mean column density $N \sim 2 \times 10^{20}$. Their mass grows by collision and merger with other CBs and by accreting the ISM gas and dust in their way. They cool by radiation until they are captured by a host star or their mass exceeds the Jeans mass and then they collapse gravitationally. After collapse they accrete rather a negligible amount of additional ISM gas and dust because of their small size.

A large fraction of the Jupiter-mass objects will end in the Galactic disk as uncollapsed Jupiter-mass gas clouds or free-floating Jupiters. Some of these Jupiters may be captured through dynamical friction, first into the Oort cloud of stars and from there into misaligned and eccentric planetary orbits. They can also kick native planets in aligned orbits around a star into misaligned orbits, particularly if they are super Jupiters. The encounter rate of
an alien planet with the Oort cloud of stars is given roughly by \( n_j \sigma v \approx 10^{-14} \text{s}^{-1} \) where we adopted a 1000 astronomical units as the effective radius of the Oort cloud and a virial velocity \( v \approx 30 \text{ km s}^{-1} \) of alien planets. Such a rate yields thousands of encounters with a star during an age comparable to the age of the Galaxy.

Uncollapsed free-floating gas clouds can also be captured by stars and be tidally disrupted into a disk with a misaligned spin-orbit around the host star, or strongly perturb their planetary system. Their star crossing rate is roughly \( n \sigma v \approx 10^{-16} \text{s}^{-1} \) where \( n \sim 200 \text{pc}^{-3} \) is their local density, \( \sigma \sim \pi 10^{30} \text{ cm}^2 \) is their cross section and \( v \sim 30 \text{ km s}^{-1} \) is their velocity. Such rates yield a high probability of Jupiter-mass clouds to be captured or strongly perturb the planetary system of most of the stars of the Galaxy during their life. Formation of planets in such misaligned disks around host stars or perturbing strongly its planetary system will result in planets with eccentric and misaligned spin-orbit.

4. Observations of alien protoplanetary disks?

The prevailing theories of planet formation posit a protoplanetary disk which is part of the protostellar disk left over after the formation of the host star. Such theories imply a close alignment between the rotation axis of the star and that of the protoplanetary disk. However, alien disks which are formed by capture of cometary blobs are expected to be warped and misaligned. Employing adaptive optics or interferometry it is possible to image some of the planet-forming disks in nearby systems and determine their alignment (Watson et al. 2010). While in some of the systems the disk is symmetrical, in others (Greaves et al. 1998; Buenzli et al. 2010; Kloppenborg et al. 2010) it is clearly lopsided, which hints at processes occurring much later than the original stellar formation. What we might be seeing in these systems is the recent capture of a cometary blob, which may form misaligned planets.

5. Free-floating planet detection through microlensing

Microlensing of stars (Liebes 1964) by planets has already been used to search for free-floating planets (Quanz et al. 2010). The effective cross section for gravitational microlensing of a star at a distance \( D_s \) by an intervening mass \( M \) at a distance \( D_l \) is given roughly by \( \sigma_l(D_l) = \pi \theta_E^2 D_l^2 \), where

\[
\theta_E = \sqrt{\frac{4 G M (D_s - D_l)}{c^2 D_s D_l}} \tag{6}
\]
is the angular radius of the Einstein ring image of the lensed star created if the lens is lying on the line of sight to the star.

The optical depth for gravitational lensing of a star in the Galactic bulge at a distance $D_s$ by free-floating Jupiters with a mass density $\rho_M[x]$ at a distance $D_l = x \, D_s$ along the line of sight to the star is given by,

$$\tau = \frac{4 G D_s^2}{c^2} \int_0^1 \rho_M[x] x (1 - x) \, dx.$$  \hfill (7)

Thus, if the mass density of planets is proportional to the stellar mass density, then they contribute to the total optical depth for microlensing in the same proportion. It follows from Eq. (7) that the optical depth for microlensing of stars in the Galactic bulge by stars along their line of sight is given approximately by

$$\tau_{\text{bulge}} \approx \frac{R_{\text{Sch}}(M_*)}{4 \pi h_r} \approx 1.7 \times 10^{-7},$$  \hfill (8)

where $R_{\text{Sch}}(M_*) = 2 G M_*/c^2 \approx 3.5 \, M_*/M_\odot$ km is the Schwarzschild radius of the total mass of the stars in the Galaxy, $M_* \approx 5 \times 10^{10} \, M_\odot$, and $h_r \approx 2.7$ kpc is the stellar scale length in the Galactic disk. This optical depth is much smaller than $\tau_{\text{bulge}} = (3.23 \pm 0.50) \times 10^{-6}$ measured by the MACHO collaboration \cite{Alcock:2000zj} and $\tau_{\text{bulge}} = (4.48 \pm 2.37) \times 10^{-6}$ measured by the OGLE collaboration \cite{Sumi:2006zz}. These measurements leave enough room for a significant contribution from free-floating Jupiters to the microlensing optical depth towards the Galactic bulge.

The typical duration of a microlensing event is the lens crossing time of the Einstein ring, $\Delta t \sim \theta_E^2 D_l/V_t$, where the $V_t$ is the lens-source relative transverse velocity observed from Earth. The typical duration of microlensing events of stars in the Galactic bulge ($D_s \approx 8$ kpc) by free floating Jupiters ($M \sim M_j \approx 0.95 \times 10^{-3} \, M_\odot$) in the Galactic bulge ($D_s - D_l \approx 1$ kpc) and for $V_t \sim 120$ km/s (the typical random velocity of stars in the Galactic bulge) is roughly,

$$\Delta t \approx \sqrt{\frac{4 G M_j (D_s - D_l)}{c^2 V_t^2}} \approx 1 \text{ day}.$$  \hfill (9)

The same lens placed at half the distance to the bulge has the maximal effective cross section for microlensing of bulge stars that is only larger roughly by a factor 2. The duration of the microlensing event is similar, $\Delta t \sim 1$ day. However, if the distribution of free floating Jupiters is proportional to that of the Galactic stars, then most of the microlensing events of bulge stars by floating Jupiters are by those present in the bulge, with a typical duration of 1 day.
For the LMC, where $M_* \approx 5.3 \times 10^9 M_\odot$ and $h_r \approx 1.6$ kpc (Alves & Nelson 2000), Eq. (7) yields an optical depth for self lensing of LMC stars by LMC stars, $\tau_{LMC} \approx 1.1 \times 10^{-8}$, while the MACHO collaboration reported (Alcock et al. 2000b; Bennett 2005) $\tau_{bulge} \approx (1.0 \pm 0.3) \times 10^{-7}$, the EROS collaboration found (Tisserand et al. 2007) $\tau_{LMC} < 3.7 \times 10^{-8}$, and the OGLE collaboration concluded (Wyrzykowski et al. 2010) that $\tau_{LMC} \approx (1.6 \pm 1.2) \times 10^{-8}$. The spread of the measured values of the microlensing optical depth towards the LMC stars and the large error bars also leave enough room for a significant contribution from free-floating Jupiters in the LMC to the microlensing optical depth of the LMC.

Although microlensing surveys seem to be promising for the search for free-floating Jupiters, they cannot detect uncollapsed Jupiter-mass clouds if their density distribution is such that their enclosed mass within a radius $r$ satisfies $M(<r) \approx (r/R) M$ (e.g., an isothermal sphere). The Einstein radius of such uncollapsed clouds (i.e., clouds with masses smaller than $\sim 0.001 M_\odot$) placed anywhere along the line of sight to the Galactic bulge is smaller than their radius of $\sim 10^{15}$ cm, at least by two orders of magnitude, which makes them practically nondetectable through gravitational lensing. However, evidence for a large Galactic population of free floating clouds with masses $M \lesssim M_J$ might come from future observations of scintillations in the radio lightcurves of galactic and extragalactic compact radio sources such as pulsars, microquasars, quasars and gamma ray bursts. Future infrared lensing surveys might also reveal free-floating Jupiter mass objects magnified by stars.

6. Evidence from scintillations of compact radio sources

Dramatic flux changes occurring over several weeks to months in the radio flux from quasars (Fiedler et al. 1987) such as 0954+658 and episodes of multiple images of radio pulsars (Cordes and Wolszczan 1986; Rickett 1990) were shown (Walker and Wardle 2010) to be reproducible by refraction from the ionized skin of an hypothesized large population of neutral clouds having a few astronomical units in radius and masses $\lesssim M_J \approx 10^{-3}$ Msun, which are free floating in the Galactic ISM and are exposed to the Galactic ionizing UV flux.

7. Conclusions

Our paper proposes a plausible common solution to two important astronomical puzzles, namely, the fate of the missing gas in galaxies and the origin of misaligned planets: Most of the baryons in galaxies may reside in Jupiter-mass objects free-floating in the ISM and not in stars. This may explain where most of the gas in galaxies has disappeared
The capture of such objects by host stars or their interaction with the planetary system of the host stars may be the main origin of misaligned planets and hot Jupiters. Modelling formation of planets by gravitational collapse is difficult, in particular the capture of free floating clouds by host stars followed by planet formation. In fact, so far numerical simulations, disputably, have not been fully successful in reproducing planet formation through gravitational instability within or without protoplanetary disks (Durisen 2005; Boley 2009; Dodson-Robinson 2009; Rafikov 2011). Observations may be a more promising route for testing the proposed ex situ origin of misaligned planets.

Compelling observational support for an ex situ origin of misaligned planets and hot Jupiters in distant orbits may come from the detection of a large population of free-floating hot Jupiters in the ISM in deep pencil searches with extremely large optical and infra-red telescopes (ELTs) equipped with advanced adaptive optics and having a much greater light collecting ability than that of the current largest telescopes. A large population of free-floating hot Jupiters in the ISM may also contribute significantly to the unresolved diffuse infra-red background radiation.

Free-floating planetary mass objects in the Galactic ISM and the Galactic halo may also be discovered through gravitational microlensing. They may explain why both the MACHO and OGLE surveys have found a total microlensing optical depth towards the Galactic bulge higher than predicted by contemporary Galactic models. The translation of the MACHO and OGLE results to a density of free-floating planet-mass objects however is sensitive to the unknown mass function of low-mass stars (red and brown dwarfs) and planets.

Future microlensing surveys will be more sensitive to free-floating planets, in particular space based surveys with telescopes such as the Wide-Field Infrared Survey Telescope (WFIRST) that unlike Kepler will be sensitive also to unbound planets. These new projects together with second generation of ground based microlensing surveys may discover a large population of free-floating planets in the Galactic ISM and determine what fraction of the missing baryons resides in such planets.

Evidence for a large population Jupiter mass clouds free floating in the Galactic ISM may come from radio and/or optical scintillations of Galactic and extragalactic sources (Walker and Wardle 2010; Draine 1998).

Alien planets, whether directly captured or formed in situ from an alien disk, can be distinguished by their unusual age, misaligned or eccentric orbit, or chemical composition. Earlier on, they can be observed as a warped gas and dust cloud caught soon after the action of collision or capture by a host star.
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The detection of a large Galactic population of unbound Jupiter mass objects, roughly twice as many as the number of main sequence stars with mass $M_1 > 0.08 M_\odot$, through microlensing observations of stars in the Galactic bulge was reported in Nature on May 19, 2011 by the Microlensing Observations in Astrophysics (MOA) collaboration and the Optical Gravitational lensing Experiment (OGLE) [Sumi et al. 2011]. The existence of such a large Galactic population of free-floating Jupiter-mass objects was suggested in this paper, which was submitted for publication in ApJ on February 13, 2011, as supportive evidence for the proposed ex-situ origin of misaligned and alien planets (fast CBs that are produced in Galactic SN explosions, but slow down sufficiently to avoid escape into the intergalactic space).

REFERENCES

Alcock, C., et al. 2000a, ApJ, 541, 734
Alcock, C. et al. 2000b, ApJ, 542, 281
Alves, D. R & Nelson, C. A. 2000, ApJ, 542, 789
Bennett D. P., 2005, ApJ, 633, 906
Bennett, D. P., 2011, AAS, 43, 21731801
Boley, A. C., 2009, ApJ, 695, L53
Catanzarite, J., 2011, AAS, 43, 21743220
Cordes, J. M. & Wolszczan, A. 1986, ApJ, 307, L27
Buenzli, E., et al. 2010, eprint, arXiv:1011.2496
Chatterjee, S., et al. 2008, ApJ, 686, 580
Close, L., 2010, Nature, 468, 1048
Creze, M., et al. 1998, A&A, 329, 920
Dodson-Robinson, S. E. et al. 2009, ApJ, 707, 79
Durisen, R. H., et al. 2005, Icar, 173, 417
Draine, B. T., 1998 ApJ, 509, L41
Fabrycky, D. & Tremaine, S. 2007, ApJ, 669, 1298
Fesen, R., et al. 2006, ApJ, 645, 283
Fesen, R., et al. 2007, ApJ, 174, 379
Ferbel, A., et al. 2007 ApJ, 660, L117
Fiedler, R. L., et al. 1987, Nature, 326, 675
Ford, E. B. & Rasio, F. A. 2008, ApJ, 686, 621
Fukugita M. & Peebles, P. J. E. 2004, ApJ, 616, 643
Greaves, J. S., et al. 1998, ApJ, 506, L133
Hebrard, G., et al. 2008, A&A, 488, 763
Hebrard, G., et al. 2011, A&A, 527, L11
Hirano, T., et al. 2010, eprint, arXiv:1009.5677
Holberg, J. B. Oswalt, T. D. & Sion, E. M. 2002, ApJ, 571, 512
Jeans, J. H. 1902, Phil. Trans. Roy. Soc. of London (Series A), 199, 1
Johnson, J. A., et al. 2009, PASP, 121, 1104
Kloppenborg, B., et al. 2010, Nature, 464, 870
Kuiper, G. P. 1951, Proc. Nat. Acad. Sc. USA, 37, 1
Liebes, S. 1964, Phys. Rev. 133, 835
Malmberg, D., et al. 2007, MNRAS, 377, L1
Matsuura, M., et al. 2007, MNRAS, 382, 1447
Matsuura, M., et al. 2009, ApJ, 700, 1067
Marois, C., et al. 2010, Nature, 468, 1080
McLaughlin, D. B. 1924, ApJ, 60, 22
Mizuno, H., 1980, Prog. Theor. Phys. 64, 544

Montmerle, T., et al. 2006, Earth, Moon, and Planets, 98, 39 and references therein.

Narita, N., et al. 2009, PASJ, 61, L35

Narita, N., et al. 2010, PASJ, 62, L61

Nero, D. & Bjorkman, J. E. 2009, ApJ, 702, L163

O’Dell, C. R., et al. 2002, AJ, 123, 3329

Pont, F., et al. 2009, A&A, 502, 695

Pont, F., et al. 2010, MNRAS, 402, L1

Quanz, S. P., et al. 2010, ApJ, 708, 770

Rafikov, R. R., 2011, ApJ, 727, 86

Rickett, B. J., 1990, ARA&A, 28, 561

Rossiter, R. A., 1924, ApJ, 60, 15

Simpson, E. K., et al., 2011, eprint, arXiv:1011.5664

Schlaufman, K. C., 2010, ApJ, 719, 602

Smith, M. C., et al. 2007, MNRAS, 379, 755

Sumi, T., et al. 2006, ApJ, 636, 240

Sumi, T., et al. 2011, Nature, 473, 349

Tamman, G. A., Loeffler, W. & Schroeder, A. 1994, ApJS, 92, 487

Tisserand, P., et al. 2007, A&A, 469, 387

Triaud, A. H. M. J., et al. 2010, A&A, 524, 25

Walker, M. & Wardle, M. 1998, ApJ, 498, L125

Watson, C. A., et al. 2010, eprint, arXiv:1009.4132

Winn, J. N., et al. 2009a, ApJ, 700, 302

Winn, J. N., et al. 2009b, ApJ, 703, 2091
Winn, J. N., et al. 2009c, ApJ, 703, L99

Winn, D., et al. 2010, ApJ, 718, L145

Wyrzykowski, L., et al. 2010, eprint, arXiv:1012.1154
Fig. 1.— An image of the Helix nebula obtained with the Subaru Telescope. At an approximate distance of 700 light years, the Helix Nebula is the closest example of a planetary nebula created at the end of the life of a Sun-like star. The most striking feature of the Helix, first revealed by ground-based images, is its collection of more than 40,000 distinct gas blobs that resemble comets due to their compact heads and long, streaming tails. Each 'cometary blob' is about twice the size of our solar system and has about an Earth’s-mass of hydrogen and other gases that were expelled from the nebula’s central star thousands of years ago. Image Credit: Matsuura, M. et al. (National Astronomical Observatory of Japan).
Fig. 2.— Hubble Space Telescope zoom on a section of the Helix Nebula showing in great detail some of its cometary blobs. The tails of these gas blobs, which resemble the much smaller solar system comets, probably, were formed by fast winds from the central star which overtook these blobs. Image Credit: Robert O’Dell, Kerry P. Handron (Rice University, Houston, Texas) and NASA.