

INTERPRETING THE M22 SPIKE EVENTS

B. SCOTT GAUDI¹

School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540; gaudi@sns.ias.edu

Received 2001 August 17; accepted 2001 October 11

ABSTRACT

Recently Sahu et al., using the *Hubble Space Telescope* to monitor stars in the direction of the old (~ 12 Gyr) globular cluster M22, detected six events in which otherwise constant stars brightened by $\sim 50\%$ during a time of $\lesssim 1$ day. They tentatively interpret these unresolved events as being caused by microlensing of background bulge stars by free-floating planets in M22. Using simple analytic arguments, I show that if these spike events are caused by microlensing, the lensing objects are unlikely to be associated with M22 and unlikely to be part of a smoothly distributed Galactic population. Thus, either there happens to be a massive dark cluster of planets along our line of sight to M22 or the spike events are not caused by microlensing. The lensing planets cannot be bound to stars in the core of M22: if they were closer than ~ 8 AU, the lensing influence of the parent star would have been detectable. Moreover, in the core of M22, all planets with separations $\gtrsim 1$ AU would have been ionized by random stellar encounters. Most unbound planets would have escaped the core via evaporation, which preferentially affects such low-mass objects. Bound or free-floating planets can exist in the outer halo of M22; however, for reasonable assumptions, the maximum optical depth to such a population falls short of the observed optical depth, $\tau \sim 3 \times 10^{-6}$, by a factor of 5–10. Therefore, if real, these events represent the detection of a significant free-floating Galactic planet population. The optical depth to these planets is comparable to and mutually exclusive from the optical depth to resolved events measured by microlensing survey collaborations toward the bulge and, thus, implies a similar additional mass of lensing objects. If the spatial and kinematic distributions of the two populations are the same, there are more than 10^3 planets per bulge microlens. Such a population is difficult to reconcile with both theory and observations.

Subject headings: globular clusters: individual (M22) — gravitational lensing — planetary systems

1. INTRODUCTION

Our understanding of the low-mass end of the compact-object mass function has seen considerable progress on many fronts in the last decade. The enormous success of radial velocity searches for extrasolar planets has improved considerably our knowledge of the statistics, distribution, and mass function of close ($a \lesssim 3$ AU) and relatively massive ($M \gtrsim 0.2 M_J$) companions to nearby stars (Marcy, Cochran, & Mayor 2000; Jorissen, Mayor, & Udry 2001; Tabachnik & Tremaine 2001). Direct searches for brown dwarf companions to local solar-type stars have led to only one detection, Gl 229B (Nakajima et al. 1995; Oppenheimer et al. 2001). Serendipitous discoveries in wide-field surveys of very low mass companions to normal stars (Kirkpatrick et al. 2001), however, have led to the conclusion that the “brown dwarf desert,” the paucity of close brown dwarf companions to stars monitored in radial velocity surveys (Marcy & Butler 2000), does not exist for wide separations (Gizis et al. 2001). The statistics of very low mass companions, $M \lesssim 10 M_\oplus$, will likely have to wait for future astrometric (Lattanzi et al. 2000) or transit-detecting (Borucki et al. 1997) satellites.

These studies have focused on GKM dwarfs in the immediate local neighborhood. Detailed studies of the parent stars of extrasolar planets have revealed that these hosts have higher metallicity in comparison to an unbiased field sample (Gonzalez 1997; Laughlin 2000). It is difficult, however, to interpret this observation, as it is not clear if the cause of this enhanced metallicity is stellar pollution from cannibalized planets or, rather, that low metallicity tends to prohibit formation (Murray et al. 2001; Santos, Israelian, &

Mayor 2001; Pinsonneault, DePoy, & Coffee 2001). In order to resolve this issue, it may be necessary to look toward other systems, such as globular clusters, open clusters, and the Galactic bulge. Such systems are useful in that they act as a control samples, where because of the homogeneous nature of the systems, one particular parameter that may affect planet formation and/or evolution (i.e., metallicity, age, local density) can be better isolated. One of the most promising methods of studying companions to stars in such systems is transits, which is in a sense ideally suited to this application since it works best when a large number of stars can be monitored simultaneously. An important null result was found when this tactic was combined with the high resolution of the *Hubble Space Telescope* (*HST*) to search for planetary companions of stars in the (relatively) metal-rich globular cluster 47 Tuc. Gilliland et al. (2000) found that the frequency of close planetary companions to stars in 47 Tuc is more than an order of magnitude smaller than in the local solar neighborhood. This lack of planets is difficult to explain in terms of dynamical stripping (Davies & Sigurdsson 2001) but may be explicable by invoking disk photoevaporation (Armitage 2000). Observations in other environments, such as the Galactic bulge (Gaudi 2000) or open clusters, have been considered, are currently being undertaken, or are being planned.

Large-scale optical and infrared surveys such as the Sloan Digital Sky Survey (SDSS) and the Two Micron All Sky Survey (2MASS) have discovered a significant population of low-mass objects. By now nearly 100 L dwarfs (Fan et al. 2000; Kirkpatrick et al. 2000) and a dozen T dwarfs (Strauss et al. 1999; Burgasser et al. 1999) are known. The difficulty with using these observations to constrain the low-mass field-object mass function is that for a given effec-

¹ Hubble Fellow.

tive temperature, there exists a degeneracy between mass and age, making the determination of the mass function fundamentally uncertain (Reid et al. 1999).

Observations of low-mass field objects confined to stellar aggregations alleviate some of these difficulties because the age of the system is known or can be estimated in many cases. Such studies have led to the detection of a population of low-mass, free-floating objects in several open clusters (Bouvier et al. 1998; Hambly et al. 1999; Zapatero Osorio et al. 2000; Martin et al. 2000). Many of these are clearly brown dwarfs, but some are suggested to have masses that place them in the canonical planet regime ($M < 13 M_J$). The relation of these objects to those found orbiting local stars is unknown, and even their designation as planets is controversial (McCaughrean et al. 2001).

Microensing is a unique method of detecting planets that offers the significant advantage that its effect is sensitive only to the mass of the lensing object and does not rely on either the flux of the planet or its parent star. Therefore, distant, extremely faint, or even completely nonluminous compact objects, either free-floating or bound to other objects, can be detected using microensing. Indeed, microensing was originally suggested by Paczyński (1986) as a method to look for dark matter in the halo of our Galaxy. In principle, extremely low mass objects can be detected, with the ultimate lower limit set by the size of the source stars. This fact was exploited by the MACHO and EROS collaborations to rule out objects having masses of 10^{-7} – $10^{-3} M_\odot$ as the primary constituents of halo dark matter (Alcock et al. 1998). The Probing Lensing Anomalies Network (PLANET) collaboration acquired and analyzed 5 years of photometric data searching for planetary companions to Galactic bulge stars, using a method first suggested by Mao & Paczyński (1991), but found no candidates, implying that $\sim M_J$ mass planets with separations of $1.5 \text{ AU} \leq a \leq 4 \text{ AU}$ occur in less than $\frac{1}{3}$ of systems (Albrow et al. 2001; Gaudi et al. 2002). Free-floating planets are also detectable in microensing searches toward the Galactic bulge (di Stefano & Scalzo 1999a). The primary drawback to using microensing to detect low-mass objects is that the mass of the lensing object typically cannot be directly measured. Instead, one measures the timescale t_E , which is a degenerate combination of the mass of the lens, and the lens-source relative parallax and proper motion. This makes unambiguous detection of low-mass objects difficult.

Recently, Sahu et al. (2001, hereafter SM22) presented an ingenious method of overcoming this difficulty, based on a suggestion originally made by Paczyński (1994). They used *HST* to monitor stars toward the old, metal-poor globular cluster M22 ($l = 9^\circ 9$, $b = -7^\circ 6$). Because M22 is projected in front of the bulge, there exists a significant probability (optical depth) that background bulge stars will be microensed by foreground M22 objects. Since the distance, velocity dispersion, and proper motion of M22 are known, the detection of a microensing event and a measurement of t_E yields a measurement of the mass of the lens, with only the unknown distance and velocity of the source contributing significantly to the error. In fact, SM22 did detect one event with $t_E = 17.6$ days, yielding a lens mass of $M = 0.13_{-0.02}^{+0.03} M_\odot$ —an impressive mass measurement of an M dwarf 2.6 kpc away.

SM22 also detected six events in which a constant light curve brightened by $\sim 50\%$ during one set of two measurements, separated by 6 minutes, and then returned to base-

line for the remaining measurements. By direct inspection of the images, SM22 rule out detector artifacts or cosmic rays as the source of these brightenings. Furthermore, the brightening was consistent in both images in each of the six cases. SM22 rule out several other astrophysical sources of variability and tentatively conclude that these brightenings are the result of unresolved microlensing events. With the sampling rate of ~ 1 per 4 days, this implies an upper limit to the timescale of $t_E \lesssim 1$ day. If the lenses are located at the distance of M22 ($D_l = 2.6 \pm 0.3$ kpc; Peterson & Cudworth 1994) and have kinematics similar to M22 stars, then this translates to an upper limit on the mass of the lenses of $M_p \lesssim 0.25 M_J$. SM22 tentatively conclude that they have found evidence for a considerable population of free-floating planets in M22. This is interesting: if every star in M22 had n_p planets of mass M_p associated with it, then the optical depth τ_p to lensing by these planets would be roughly given by

$$\tau_p \approx \frac{M_p}{M_*} n_p \tau_*, \quad (1)$$

where M_* is the mass of a typical star in M22 and τ_* is the lensing optical depth to normal stars. Therefore, for $M_p \leq 0.25 M_J$ and $\tau_* \simeq 10^{-5}$ for the core of M22 (see § 5), $\tau_p \lesssim 10^{-8} n_p$. Since SM22 monitored $\sim 8 \times 10^5$ stars, detecting any events would be very unlikely unless n_p is very large. Indeed, SM22 estimate that 10% of the cluster mass may be in these planetary objects.

De la Fuente Marcos & de la Fuente Marcos (2001) discuss some of the implications of this inference. By analyzing a suite of N -body simulations, they argue that the majority of planets in the core of M22 will be ionized from their parent stars and those ionized planets will quickly evaporate from the core. They argue that bound planets may be able to survive in the outskirts of M22, thus reproducing the observed optical depth, but only if multiplanet systems are common. They favor the possibility, however, that these events are the result of a dark cluster of planets not associated with the globular cluster.

Because microensing events do not repeat, the only way to verify these observations directly is to perform the same experiment at even higher time resolution. Since this experiment essentially requires the resolution of *HST*, this would be a major investment of limited resources. Given the importance of this result on the one hand and the considerable expenditure of resources required for direct verification on the other, it seems prudent to consider the SM22 interpretation of these spike events in more detail. Here I present such a study, which is complementary to that presented by de la Fuente Marcos & de la Fuente Marcos (2001) in that I rely primarily on analytic arguments (rather than on the results of N -body simulations). In § 2, I briefly review the SM22 observations and collect some relevant parameters for M22. In § 3, I review the basics of microensing and apply these to the M22 observations in § 3.1. In § 4, I show that these objects are unlikely to be associated with M22, by first demonstrating that these planets must be separated by $a \gtrsim 8$ AU from their parent stars (§ 4.1), by second showing that planets in the core with separations $a \gtrsim 0.3$ AU would be ionized by other stars (§ 4.2), by third showing that most low-mass, free-floating planets would have evaporated from the cluster core over the cluster lifetime (§ 4.3), and finally by showing that the maximum optical depth to planets in the

TABLE 1
MEASURED AND ESTIMATED PARAMETERS FOR THE M22 EVENTS

Source	m_{F606W}	m_{F814W}	Δm_{F814}	A	$(m_{F606W} - m_{F814W})_0^a$	M_{F814W}^b
Fig. 1.....	18.86	17.85	0.70	2.70
A.....	23.32	21.64	-0.46	1.53	1.37	6.49
B.....	23.81	22.25	-0.46	1.53	1.25	7.10
C.....	23.51	22.12	-0.72	1.94	1.08	6.97
D.....	22.70	21.33	-0.31	1.33	1.06	6.18
E.....	23.03	21.49	-0.49	1.57	1.23	6.34
F.....	22.14	20.81	-0.31	1.33	1.02	5.66

^a Dereddened color assuming $E(B-V) = 0.634$, or $E(F606W - F814W) = 0.31$.

^b Absolute magnitude assuming a distance modulus of 14.52 and $E(B-V) = 0.634$.

halo of M22 falls considerably short of the observed optical depth (§ 4.4). Thus, if the spike events are indeed the result of microlensing, the lensing objects cannot be associated with M22. In § 5, I explore the implications of this conclusion and show that if smoothly distributed, the implied free-floating Galactic planet population is hard to reconcile with current theoretical and observational constraints. Thus, either the explanation of de la Fuente Marcos & de la Fuente Marcos (2001) is correct—there is a dark cluster of planets along our line of sight to M22—or the majority of the spike events cannot be caused by microlensing. In light of the circumstantial evidence against the microlensing interpretation of these events, in § 6 I present a critical reevaluation of the direct evidence in favor of microlensing. I summarize and conclude in § 7.

2. OBSERVATIONS AND M22 PARAMETERS

SM22 monitored the central region of M22 with *HST* over the course of 114 days with a total of 43 epochs, with three fields monitored at each epoch. The majority of the measurements was taken in the F814W (*I*) filter with every fourth measurement in the F606W (wide *V*) filter. I will be primarily considering the light curves presented in Figure 2 of SM22, which show the F814W-band light curves of the six spike events over a period of 105 days, with ~ 25 measurements in each light curve, for a sampling interval of ~ 4 days. The typical photometric errors for these light curves, as judged by the scatter, is 1%–5%. Table 1 gives the baseline F814W and F606W magnitudes of these six spike events, reproduced from Table 1 of SM22 and retaining

TABLE 2
COLLECTED RELEVANT PARAMETERS FOR M22

Parameter	Symbol	Value	Reference
Distance.....	D_l	2.6 kpc	1
Core radius.....	r_c	1'4	2
Tidal radius.....	r_t	28'9	2
Central density.....	ρ_0	$4.65 \times 10^3 M_\odot \text{pc}^{-3}$	3
Velocity dispersion.....	σ	11.4 km s ⁻¹	1
Proper motion.....	μ_l	10.9 mas yr ⁻¹	1
Age.....	T_0	12 Gyr	4
Typical mass.....	M_*	0.33 M_\odot	5
Reddening.....	$E(B-V)$	0.326	6
Galactic coordinates.....	(l, b)	(9°9, -7°6)	
Metallicity.....	[Fe/H]	-1.54 ± 0.11	7

REFERENCES.—(1) Peterson & Cudworth 1994; (2) Trager et al. 1995; (3) Peterson & King 1975; (4) Davidge & Harris 1996; (5) Paresce & De Marchi 2000; (6) Schlegel et al. 1998; (7) Lehnert, Bell, & Cohen 1991.

their lettering scheme. Also presented in Table 1 are estimates of the amount by which these events brightened, both in magnitudes, Δm_{F814W} and the corresponding magnification A assuming no blending.² Values for Δm_{F814} have errors of 2%–7%, as estimated by eye. Finally, Table 1 shows the dereddened color and absolute magnitude of the SM22 sources, assuming they are located at the Galactic center, i.e., a distance modulus of 14.52 (8 kpc), and $E(B-V) = 0.326$. The latter was found using the reddening maps of Schlegel, Finkbeiner, & Davis (1998). This value agrees well with that reported by Piotto & Zoccali (1999) from main-sequence fitting to M22 and translates to $A_{F606W} = 0.94$ and $A_{F814W} = 0.63$.

Table 2 lists parameters of M22 collected from various sources in the literature that will be relevant to the discussion. In some cases there are discrepancies in the published literature. Where possible, I have adopted the most modern determinations. Adopting other values for these parameters will change some of the resulting computations in detail but will not affect the general arguments and conclusions.

3. MICROLENSING BASICS

In this section I review the fundamentals of microlensing, concentrating on those concepts that are important for the present study. A lens of mass M at a distance D_l has an angular Einstein ring radius of

$$\theta_E = \sqrt{\frac{4G}{c^2} \frac{M}{D_{\text{rel}}}} \simeq 0.834 \text{ mas} \left(\frac{M}{0.33 M_\odot} \right)^{1/2}, \quad (2)$$

where D_{rel} is defined by

$$\frac{1}{D_{\text{rel}}} \equiv \frac{1}{D_l} - \frac{1}{D_s}, \quad (3)$$

and D_s is the distance to the source. The scaling relation at the extreme right-hand side of equation (2), as well as all scaling relations presented in this section, are appropriate for M22 parameters, i.e., $D_l = 2.6$ kpc, $D_s = 8.0$ kpc. At the distance of the lens, θ_E corresponds to a physical distance of

$$R_E = \theta_E D_l \simeq 2.17 \text{ AU} \left(\frac{M}{0.33 M_\odot} \right)^{1/2}. \quad (4)$$

² For typical ground-based resolutions ($\sim 1''$), a large fraction of sources are blended, i.e., there exist multiple stars in each resolution element (Han 1997a). With the resolution of *HST*, however, essentially all stars are resolved (Han 1997b). Thus, the observed flux is most likely directly related to the magnification, unless the lens itself or an unlensed companion to the source or lens is of comparable brightness to the lensed source.

The timescale of a microlensing event is given by

$$t_E = \frac{\theta_E}{\mu_{\text{rel}}} \simeq 27.9 \text{ days} \left(\frac{M}{0.33 M_\odot} \right)^{1/2}, \quad (5)$$

where μ_{rel} is the lens source relative proper motion. I will assume that the mean source proper motion is zero (which is appropriate for sources in the bulge), and thus $\mu_{\text{rel}} = \mu_l = 10.9 \text{ mas yr}^{-1}$.

The foreground lens magnifies the background source by an amount that depends only on the angular separation θ between the lens and source in units of θ_E , $u \equiv \theta/\theta_E$. For a single lens the magnification is

$$A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}. \quad (6)$$

In particular, $A(1) = 3/\sqrt{5} \simeq 1.34$. For a simple microlensing,

$$u(t) = [u_0^2 + t_E^{-2}(t - t_0)^2]^{1/2}, \quad (7)$$

where t_0 is the time of maximum magnification and u_0 is the impact parameter. Note that u_0 is distributed uniformly.

The optical depth to microlensing, τ , defined as the probability that any star is magnified by more than 1.34, is given by

$$\tau = \frac{4\pi G}{c^2} \int_0^{D_s} dD_l \rho(D_l) D_{\text{rel}}, \quad (8)$$

where ρ is the mass density along the line of sight to the source.

Observationally, the optical depth can be estimated from a sample of N_e events with measured timescales $t_{E,i}$ by

$$\tau_{\text{obs}} = \frac{\pi}{2N_* \Delta t} \sum_{i=1}^{N_e} \frac{t_{E,i}}{\epsilon_i}, \quad (\text{resolved events}) \quad (9)$$

where N_* is the number of stars monitored for a duration Δt and ϵ_i is the detection efficiency of event i . As is shown in § 3.1, the expression for unresolved events (where t_E is not known) takes a slightly simpler form.

3.1. Application to the M22 Events

Before discussing constraints on the location of the lenses, I first apply the microlensing formalism just presented to the M22 events. SM22 reports that the single resolved event has a timescale of $t_E = 17.6$ days. Assuming that the lens is associated with M22 and that the source is in the bulge, this translates into a mass of $M = 0.13 M_\odot$ (eq. [5]). Careful accounting of the dispersion in bulge source distances and kinematics establishes an error of $\sim 15\%$ (SM22). Inspecting the mass function (MF) of M22 as determined by Paresce & De Marchi (2000), the number of stars with this mass is approximately 20% smaller than at the peak of the MF ($M = 0.33 M_\odot$). One would expect $\sim 0.8(0.13/0.33)^{1/2} \sim 50\%$ fewer events from objects with $M = 0.13 M_\odot$ than the peak of the MF, and thus the derived mass is quite plausible. The optical depth implied by this one resolved event ultimately depends on the detection efficiency, but a lower limit can be found by assuming $\epsilon = 1$. Because of the high quality of the *HST* photometry, the fact that the sampling interval is considerably less than t_E , and that blending is likely not an issue, the true optical depth is probably not much larger than this lower limit.

I find

$$\tau_{\text{res}} \gtrsim 3 \times 10^{-6}, \quad (10)$$

where I have adopted $N_* = 83,000$, as indicated by SM22, and $\Delta t = 105$ days, which is derived from their Figures 1 and 2. As I show in § 4.4, this lower limit is a factor of ~ 3 smaller than would be expected based on what we think we know about the central density and structure of M22. This could be caused by inaccurate parameters for M22, an efficiency considerably smaller than unity, or Poisson fluctuations. The one resolved event is somewhat unusual because the source is reported to be a variable. In fact, in order to derive t_E from the light curve, SM22 fit the event to a binary-source model. This provides a consistency check on the microlensing interpretation, as the binary-source model provides a limit on θ_E that can be compared with the value derived from the timescale (Han & Gould 1997; Alcock et al. 2001).

Obviously the timescales of the six unresolved events are unknown. SM22 assert that the statistical upper limit to t_E is 0.8 days (at a 95% confidence level), which translates to $M \leq 0.27 \times 10^{-4} M_\odot$ or $M \lesssim 0.25 M_J$, where M_J is the mass of Jupiter. A lower limit to the mass can be derived by considering finite source effects, and is $M \gtrsim 3 \times 10^{-8} M_\odot$, or about the mass of the Moon. The reason that this limit is not very restrictive is that the source stars are K and M dwarfs, which are relatively small. Although the timescales of the events are unknown, the optical depth can still be estimated. In the limit of unresolved (“spike”) events, the optical depth becomes

$$\tau_{\text{obs}} = \frac{N_{\text{spike}}}{N_* N_d} \frac{1}{\min(1, u_T^2)}, \quad (\text{spike events}) \quad (11)$$

where N_{spike} is the number of spike events having $A > 1.34$, N_d is the number of epochs per light curve, u_T is

$$u_T = \sqrt{2[(1 - A_T^{-2})^{-1/2} - 1]^{1/2}}, \quad (12)$$

and A_T is the minimum detectable magnification. In the case of the six spike events, $u_T > 1$, and thus the optical depth is simply $\tau_{\text{obs}} = N_{\text{spike}} N_*^{-1} N_d^{-1}$. Adopting $N_d = 25$,

$$\tau_{\text{spike}} = (2.9 \pm 1.2) \times 10^{-6}, \quad (13)$$

where the error is that due solely to Poisson statistics. The optical depth to the single resolved event can also be estimated using equation (11), simply by setting N_{spike} equal to the number of data points on the event light curve with magnification greater than 1.34, restricting attention to those taken in the F814W filter. Since there are six such points, this results in the same optical depth as τ_{spike} , in excellent agreement with the optical depth estimated from the usual formula. Thus the optical depth due to the spike events is comparable to that contributed by the one resolved event. If the spatial and kinematic properties of the two samples are the same, this implies a similar mass in each component.

4. BINARY LENSES, IONIZATION, AND EVAPORATION

4.1. Binary Lenses

All six of the spike events discovered by SM22 are well characterized by a flat light curve (to within the photometric errors) with one deviant data point. As pointed out by SM22, the fact that the light curve exhibits no features other than the one deviant point implies that the planet

must be quite distant from any parent star or the lensing influence of the primary would be detectable. The minimum separation compatible with the data depends on the mass of the primary and the photometric accuracy, σ_p . Formally, the lensing behavior of the planet bound to a parent star is described by the formalism of binary lenses (Mao & Paczyński 1991; Gould & Loeb 1992). However, when the projected separation of the planet and star separation in units of θ_E is much larger than the Einstein ring radius of the system, the magnification structure is well described by the superposition of two point masses (di Stefano & Mao 1996; di Stefano & Scalzo 1999b) separated by a distance of $\tilde{d} = (d^2 - 1)/d$, where d is the instantaneous angular separation of the planet and star in units of θ_E (Gaudi & Gould 1997). The detection probability is roughly the probability that the source trajectory will pass within u_T of the primary lens multiplied by the probability that the deviation due to the primary occurs during the observation window. Assuming that the mass of the secondary is much smaller than the mass of the primary, that the times of maximum magnification of the planetary events are uniformly distributed in the observation window, and normalizing all distances to the mass of the primary, the detection probability is

$$P_{\text{det}}(d) = \begin{cases} 1 & \text{if } \tilde{d} \leq u_T, \\ \frac{2}{\pi} \left(1 - \frac{\tilde{d} - u_T}{\Delta u}\right) \arcsin\left(\frac{u_T}{\tilde{d}}\right) & \text{if } u_T < \tilde{d} < u_T + \Delta u, \\ 0 & \text{if } \tilde{d} \geq u_T + \Delta u, \end{cases} \quad (14)$$

$\Delta u \equiv \Delta t/t_E$, and t_E is the timescale of the primary. In order to convert from the detection probability as a function of d to the detection probability as a function of the semimajor axis a of the planet, it is necessary to convolve $P_{\text{det}}(d)$ with the probability of d given $a_p \equiv a/R_E$:

$$P_{\text{det}}(a_p) = \int_0^{a_p} dd P_{\text{det}}(d) P(d; a_p), \quad (15)$$

where

$$P(d; a_p) = \frac{d}{a_p} \left(1 - \frac{d^2}{a_p^2}\right)^{1/2}, \quad (16)$$

(Gould & Loeb 1992). $P_{\text{det}}(a_p)$ can be converted to physical units by adopting a value for R_E . Figure 1 shows $P_{\text{det}}(a)$ as a function of a assuming a primary of mass $M = 0.33 M_\odot$ and $A_T = 1 + \sigma_p$, with $\sigma_p = 1\%$, 5% , and 10% . The 95% confidence level (cl) lower limit on a is the value where $P_{\text{det}}(a) = 1 - 0.05^{1/6} \simeq 40\%$. I find

$$a \geq 7.5 \text{ AU} \quad (95\% \text{ cl}) \quad (17)$$

for $\sigma_p = 10\%$. Figure 1 also shows the results of computing $P_{\text{det}}(a_p)$ adopting the full binary formalism (Witt 1990), which gives nearly identical results.

The lower limit given in equation (17) is somewhat model dependent; adopting a smaller mass for the primary would lower the limit. The estimate is conservative, however, as I have assumed that the magnification from the primary must rise above A_T for it to be detected when, in fact, the cumulative effect of the curvature due to the primary on the light curve may make it detectable for separations considerably larger than those calculated using equation (14).

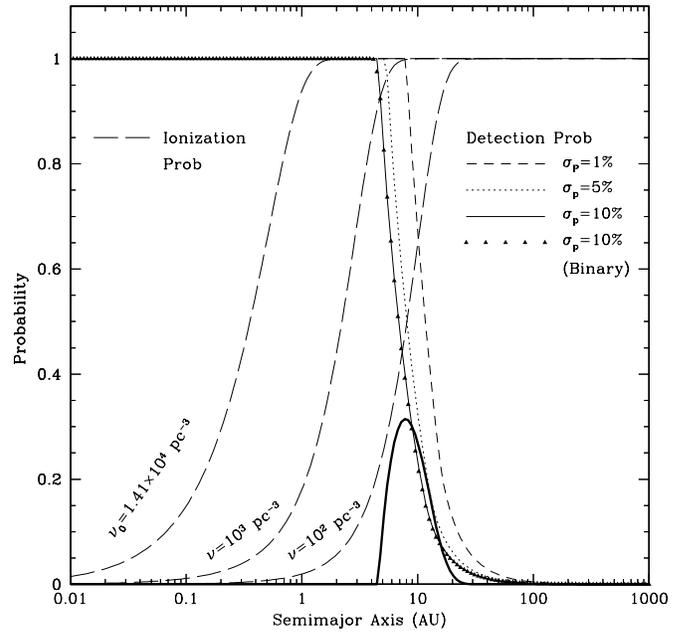


FIG. 1.—Long-dashed curves show the ionization probability P_{ion} as a function of semimajor axis, assuming a cluster age of $T_0 = 12$ Gyr, a velocity dispersion of $\sigma = 11.4 \text{ km s}^{-1}$, and stellar densities of (left to right) $\nu = 1.41 \times 10^4$, 10^3 , and 10^2 pc^{-3} . The solid, dotted, and short-dashed curves show the primary detection probability P_{det} as a function of the semimajor axis of the planet for photometric errors of $\sigma_p = 1\%$, 5% , and 10% , respectively. The triangles show the detection probability for $\sigma_p = 10\%$ using the full binary-lens formalism. The heavy solid curve is the probability of not being ionized and not being detected, i.e., $(1 - P_{\text{ion}})(1 - P_{\text{det}})$, for $\sigma_p = 10\%$ and $\nu = 10^2 \text{ pc}^{-3}$.

Note that de la Fuente Marcos & de la Fuente Marcos (2001) give a lower limit on a that is a factor of ~ 2 smaller than equation (17). This is because of the fact that they adopt a rather different—and considerably more conservative—detection criterion than assumed here. They require that $d \leq u_T$ for the primary to be detected. This requirement gives the absolute lower limit on d in the sense that the primary will be detectable in essentially all trajectories if $d \leq u_T$. For larger d , however, a fraction $P_{\text{det}}(d)$ of trajectories should show evidence for a primary. Thus, the lack of detections in six events can be used to place a more stringent lower limit.

4.2. Ionization

In dense stellar environments, such as the core of M22, planetary systems cannot be treated as isolated. The large number density and velocity dispersion imply that a star is likely, within the lifetime of the cluster, to encounter another star. Such encounters will inevitably lead to stripping off of weakly bound outer planets, i.e., ionization.

The average number of encounters a given planetary systems has with a field star per unit time is given by $1/t_{\text{enc}}$, where t_{enc} is the encounter time (Binney & Tremaine 1997):

$$t_{\text{enc}} = \left[16\sqrt{\pi}\nu\sigma a^2 \left(1 + \frac{GM_*}{2\sigma^2 a}\right) \right]^{-1}, \quad (18)$$

where ν is the local number density. For $a = 1 \text{ AU}$, and assuming parameters appropriate for M22, $t_{\text{enc}} = 4.3 \text{ Gyr} (\nu/1.41 \times 10^4 \text{ pc}^{-3})^{-1}$. Thus, in the core of M22, every star is likely to experience an encounter with another star with an impact parameter $\leq 1 \text{ AU}$ during the lifetime of

the cluster. According to Heggie's law, soft binaries will tend to get disrupted by such encounters. The binary is soft if $a > a_{h/s}$, where

$$a_{h/s} = \frac{2GM_p}{\sigma^2} \simeq 3 \times 10^{-3} \text{ AU} \frac{M_p}{0.25 M_J} \left(\frac{\sigma}{11.4 \text{ km s}^{-1}} \right)^{-2}, \quad (19)$$

and I have assumed that the mass of the planet, M_p , is much smaller than the field and parent star masses, which I have assumed to be equal. Thus, essentially all planetary systems are soft and will be disrupted on a timescale t_{enc} . I therefore write the ionization probability as a function of a as

$$P_{\text{ion}}(a) = 1 - e^{-T_0/t_{\text{enc}}(a)}. \quad (20)$$

This probability is shown in Figure 1 for three different values of the number density. Equations (18) and (20), although crude, agree well with more detailed and realistic calculations (Smith & Bonnell 2001; Bonnell et al. 2001; Davies & Sigurdsson 2001). For the core of M22 ($\nu = 1.41 \times 10^4 \text{ pc}^{-3}$), the upper limit to the separation of a bound planet is

$$a \leq 0.3 \text{ AU} \quad (95\% \text{ cl}). \quad (21)$$

Comparing equations (21) and (17), it is clear that the spike events cannot be the result of planets bound to stars in the core of M22.

There are several caveats. First is that I have not considered the possibility of exchanges due to encounters, i.e., where the planet is transferred from the original parent star to the field star as a result of the encounter rather than being ionized completely. The timescale for exchange is (Hut & Bahcall 1983; Hut 1983)

$$t_{\text{ex}} = \frac{3\sigma^5 a}{20\pi\nu G^3 M_*^3}, \quad (22)$$

where I have again assumed that the mass of the planet is much smaller than that of the field and parent stars, with the latter two masses to be equal. For conditions in the core of M22, $t_{\text{ex}} = 1.1 \text{ Gyr}(a/\text{AU})(\nu/1.41 \times 10^4 \text{ pc}^{-3})^{-1}$. The ratio of the exchange to encounter timescales is given by

$$\frac{t_{\text{ex}}}{t_{\text{enc}}} \simeq 0.25 \left(\frac{a}{\text{AU}} \right)^3, \quad (23)$$

where I have neglected the term in t_{enc} due to gravitational focusing. Note that $t_{\text{ex}}/t_{\text{enc}}$ is independent of ν . For $a \gtrsim 1.6 \text{ AU}$, the rate of encounters will exceed the rate of exchanges, and the net effect of encounters will be to ionize planets completely. Since this is safely below the lower limit on a set in § 4.1, exchanges can be ignored.

The second caveat is that I have not considered processes that may create planetary systems, such as three-body interactions (Heggie 1975) and tidal capture (Fabian, Pringle, & Rees 1975; Press & Teukolsky 1977; Lee & Ostriker 1986). In fact, it can be shown that all such processes are extremely subdominant, and the net result of dynamical interactions on soft binaries is disruption (see Appendix 8.B of Binney & Tremaine 1997).

4.3. Evaporation

Some fraction of the planets that are ionized from their parent stars will have, upon ionization, speeds exceeding the

local escape speed, which for the core is $v_e \simeq 23 \text{ km s}^{-1}$ (Peterson & Cudworth 1994). These planets will rapidly escape the cluster on a timescale of order the crossing time, $t_{\text{cross}} = r_t/v_e \simeq 1 \text{ Myr}$. However, this will constitute a very small fraction of all ionized planets. The majority of the ionized planets will remain bound to the cluster with velocities similar to the velocities of their parent stars. Over the lifetime of the cluster, these free-floating planets will undergo many encounters with the cluster's stellar population. These encounters will tend to drive the system toward equipartition, so that $\sigma_p^2 \sim (M_*/M_p)\sigma_*^2$, where σ_* is the velocity dispersion of the stars. If the cluster mass is dominated by the stellar component, i.e., the total mass in planets is negligible, then the potential will be determined by the stars, and the local velocity dispersion σ of the cluster will be σ_* . In this case, it is clear that equipartition cannot actually be realized, since $M_*/M_p > 4$, and hence the planets will attain velocities larger than the local escape speed, $\sigma_p > 2\sigma = v_e$, and thus escape from the system.

The timescale over which the planets get ejected from the system is the relaxation time (Spitzer 1987):

$$t_{\text{relax}} = 0.065 \frac{\sigma^3}{\nu M_*^2 G^2 \ln \Lambda}, \quad (24)$$

where $\ln \Lambda$ is the Coulomb logarithm, which I will take to be $\ln \Lambda = \ln(0.4 N_*) = \ln(4\pi\nu_0 r^3/3) \simeq 10$. Here N_* is the total number of stars in the system. For the core of M22, $t_{\text{relax}} = 0.33 \text{ Gyr}$. Thus, assuming a constant density and velocity dispersion, the core has experienced ~ 35 relaxation times during the lifetime of the cluster. Therefore, all planets should have long since evaporated from the cluster core.

Note that equation (24) is the relaxation time for the stars, which is appropriate for the planets only if the mass in planets is much smaller than that in stars. In the case when the two mass components are comparable, one might be tempted to adopt the equipartition timescale (Spitzer 1969)

$$t_{\text{eq}} = \frac{\sigma^2}{4\sqrt{3}\pi G^2 M_* M_p \nu \ln N} \simeq \frac{M_*}{M_p} t_{\text{relax}}. \quad (25)$$

As argued before, however, the system cannot actually achieve equipartition because $M_*/M_p > 4$. Thus, the estimate in equation (25) breaks down and the true evaporation timescale will be considerably smaller. Regardless, if the mass in planets were comparable to that in stars today, M22 should exhibit a relatively large mass-to-light ratio, since planets of $M_p \simeq 0.25 M_J$ emit very little light. Peterson & Cudworth (1994) find a global mass-to-light ratio of $M/L \lesssim 1$ for M22, which is anomalously low for globular clusters and not compatible with a substantial population of planets by mass. Therefore, equation (24) should be applicable.

4.4. Planets in the Halo of M22?

The results of §§ 4.1, 4.2, and 4.3 show that a significant population of planets, either bound or free floating, cannot exist in the core of M22 (and explain the spike events). However, the relevant timescales, t_{enc} and t_{relax} , are both inversely proportional to the stellar density ν , which drops precipitously outside the cluster core, typically as $\nu \propto r^{-3}$, where r is the radial distance from the center of the cluster. For the low-density outskirts of the cluster, the encounter

and relaxation timescales can be larger than the lifetime of the cluster, and bound and free-floating planets can survive.

Figure 1 shows t_{enc} for stellar densities of $\nu = 10^3 \text{ pc}^{-3}$ and 10^2 pc^{-3} . For very low densities, bound planets are in principle compatible with the observed spike events. For example, for $\nu = 10^2 \text{ pc}^{-3}$ there exists a range of a (albeit a small one) where bound planets could survive ionization and yet still satisfy the lower limit of $a > 7.5 \text{ AU}$ set by the lack of detection of the parent star.

Similarly, for the outskirts of the cluster the relaxation time can exceed the lifetime of the cluster. Specifically, assuming σ is constant throughout the cluster, $t_{\text{relax}} > T_0$ for $\nu \lesssim 5.5 \times 10^2 \text{ pc}^{-3}$. In these regions free-floating planets will evaporate very slowly.

Can the bound or free-floating planets in the halo of M22 explain the measured optical depth? The answer will depend on the competition between the declining contribution to the optical depth from the outer parts of the halo and the increasing longevity of bound and/or free-floating planets. Therefore, it is necessary to assume a form for the density profile of M22. I will adopt the following form:

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3/2}. \quad (26)$$

Although it is a good match to observed cluster properties, this form has the disadvantage that the total enclosed mass diverges logarithmically. For practical purposes, I will denote the total cluster mass as the mass interior to r_t . From this form, the projected mass density, $\Sigma(r)$, as a function of the projected distance from the cluster center, can be derived:

$$\Sigma(r) = 2\rho_0 r_c \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-1}. \quad (27)$$

Figure 2 shows $\rho(r)$, $\Sigma(r)$, $\sigma(r)$, and $M(r)$ as a function of r/r_c . For M22, the concentration is $c = \log(r_t/r_c) = 1.31$, and $r_t = 20.4r_c$ is just at the edge of the figure.

From equation (8), and given that the size of the cluster is small compared to D_s , the optical depth to microlensing is

$$\tau = \frac{4\pi G \Sigma D_s}{c^2} x(1-x), \quad (28)$$

where $x \equiv D_l/D_s$. Inserting values appropriate for M22, and adopting the form for $\Sigma(r)$ given in equation (27), I find

$$\tau_{\text{tot}} \simeq 10^{-5} \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-1}, \quad (29)$$

where r refers to the projected distance from the cluster center. Note that this overestimates the optical depth slightly, since the form of $\Sigma(r)$ given in equation (27) is found from integrating the density along the line of sight from $-\infty$ to ∞ , when in fact the integral should be cut off at the tidal radius r_t . The difference is negligible except near projected distances of $r \sim r_t$, where the optical depth is extremely small anyway. The optical depth as a function r is shown in Figure 3. The *HST* observations of SM22 were concentrated in the inner $\sim 2/5$ of M22. In this region, $\tau \simeq 10^{-5}$, which is a factor of ~ 3 times larger than the minimum optical depth estimated from the single resolved event (see § 3.1).

What fraction of optical depth can be contributed by planets? Assume some fraction f_p of the cluster mass density was originally in the form of planets. For simplicity, I will

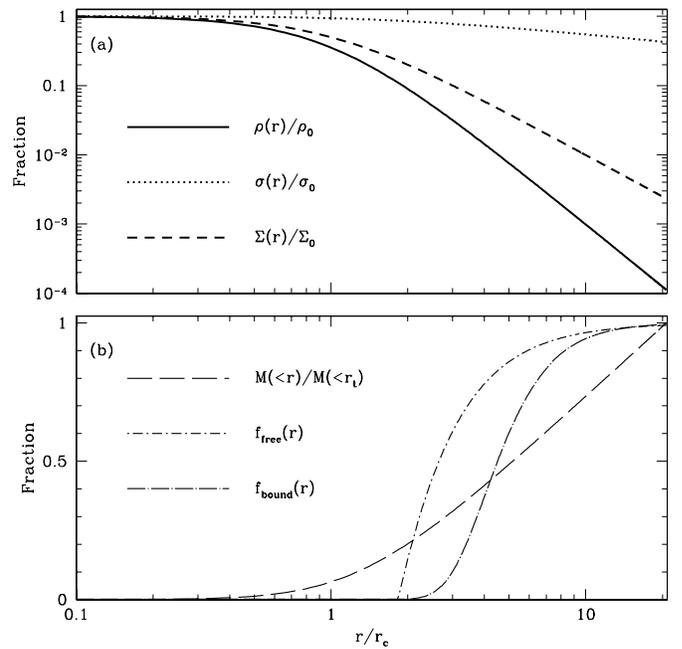


FIG. 2.—(a) The solid curve shows the physical density $\rho(r)$ normalized to the central density ρ_0 as a function of radius from the center of the cluster, r , normalized to the core radius r_c , for a model with $\rho(r) = \rho_0 (1 + r^2/r_c^2)^{-3/2}$. For M22, $\rho_0 = 4.65 \times 10^3 M_\odot \text{ pc}^{-3}$, $r_c = 1/4$, and the tidal radius is $r_t = 29/0 \simeq 21r_c$ (at the right edge of the figure). The dotted line shows the local velocity dispersion σ normalized to the central velocity dispersion σ_0 . The short-dashed line shows the projected mass density $\Sigma(r)$, where r now refers to the projected distance from the cluster center. (b) The long-dashed line in the mass $M(<r)$ interior to r , normalized to $M(<r_t)$, the total mass interior to the tidal radius, r_t . The dot-short-dashed line shows f_{free} , the fraction of free-floating planets that have survived evaporation. The dot-long-dashed line shows f_{bound} , the fraction of systems that remain bound.

assume that this fraction is universal, i.e., the primordial mass density in planets is simply $\rho_p(r) = f_p \rho(r)$. I will further assume that f_p is sufficiently small that the dynamics of the cluster is everywhere dominated by the stellar component, and furthermore that the cluster has not evolved significantly during its lifetime (almost certainly an oversimplification). The fraction of bound planets that will have survived ionization due to stellar encounters is simply

$$f_{\text{bound}}(r; a) = 1 - P_{\text{ion}}(r; a) = e^{-T_0/t_{\text{enc}}}, \quad (30)$$

where P_{ion} is given in equation (20), and the dependence on r arises because t_{enc} depends on ν and σ . An upper limit on $f_{\text{bound}}(r)$ is found by inserting $a = 7.5 \text{ AU}$, which is the lower limit on a set by the lack of detection of the primary in the spike events (§ 4.1). The fraction of free-floating planets that have survived evaporation from the cluster is

$$f_{\text{free}}(r) = 1 - \frac{\xi_e T_0}{t_{\text{relax}}}, \quad (31)$$

where ξ_e is the evaporation probability. Equation (31) implies a linear dependence of the mass loss on time, as derived analytically for tidally truncated clusters by Spitzer (1987), and found numerically from the detailed evolutionary models (Chernoff & Weinberg 1990; Vesperini & Heggie 1997). For a relaxed system, ξ_e can be estimated as the fraction of stars in a Maxwellian velocity distribution that have velocities greater than $v_e = 2\sigma$, which is $\xi_e = 7.4 \times 10^{-3}$. This is certainly an underestimate for the evaporation probability of the planets, however, because equi-

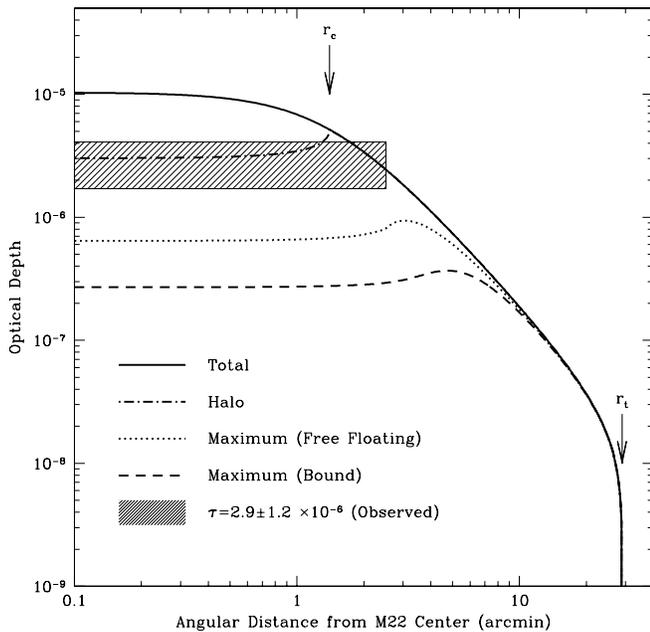


FIG. 3.—Solid line shows the total optical depth τ_{tot} as function of angular distance from the center of M22 in arcminutes for the model shown in Fig. 2. The core radius ($r_c = 1.4$) and tidal radius ($r_t = 28.9$) are marked with downward-pointing arrows. The shaded box shows the inferred optical depth and error from the six spike events, $\tau_{\text{spike}} = (2.9 \pm 1.2) \times 10^{-6}$. The angular extent of the box is the longest width of the WFPC2 camera, 2.5, and roughly corresponds to the region surveyed by SM22. The dotted line is the maximum optical depth from free-floating planets in such a model. The dashed line is the maximum optical depth from bound planets. The dash-dotted line is the halo contribution to the total optical depth.

partition will drive them to significantly higher velocities than the mean σ . I adopt the value of $\xi_e = 0.156$ for test masses given in Spitzer (1987), as derived from the models of Hénon (1961). Note that this value of ξ_e is the global probability for the cluster referenced to the half-mass relaxation time, whereas for this calculation an estimate of the local evaporation probability, referencing to the local relaxation time t_{relax} is necessary. I will simply assume the global value of $\xi_e = 0.156$ is appropriate, but note that this may be slightly in error.

The optical depth contributed from bound planets can now be estimated:

$$\tau_{\text{bound}} = \frac{4\pi G D_s^2}{c^2} x(1-x)f_p \left[\int ds \rho(s) f_{\text{bound}}(s) \right], \quad (32)$$

where the integral is along the line of sight over the extent of the cluster. The expression for τ_{free} is the same, but with f_{bound} replaced by f_{free} . The value for f_p , the fraction of the original cluster mass in planets, is unknown. Therefore, I will simply consider the maximum optical depth, which is found by setting $f_p = 1$. Note that this is truly a limit in the sense that it does not actually correspond to a self-consistent physical picture. I discuss this in more detail below.

The resulting maximum optical depths to bound planets, $\tau_{\text{bound}}^{\text{max}}$, and to free-floating planets, $\tau_{\text{free}}^{\text{max}}$, are shown in Figure 3. For observations within the central $\sim 2'$ of M22, $\tau_{\text{bound}}^{\text{max}} = 6.4 \times 10^{-7}$ and $\tau_{\text{free}}^{\text{max}} = 2.7 \times 10^{-7}$. These upper limits are ~ 5 and ~ 10 times smaller than the optical depth inferred from all six spike events, $\tau_{\text{spike}} \simeq 3 \times 10^{-6}$, and are only marginally consistent with the optical depth contributed by

just one event. Note that such models require that the outer 70% of the cluster be *entirely* composed of planets.

How sensitive are the results to the adopted form for the density profile? For isolated clusters, the density should fall off as $\rho(r) \propto r^{-3.5}$ in the outer halo (Spitzer & Thuan 1972), whereas tidally truncated clusters will exhibit somewhat shallower profiles (Chernoff & Weinberg 1990). Both of these profiles are steeper than the $\rho(r) \propto r^{-3}$ behavior exhibited by the model adopted here. Indeed, the surface brightness profile of M22 falls off as $\mu(r) \propto r^{-2.2}$ in the outer halo (Trager, King, & Djorgovski 1995), somewhat steeper than the $\Sigma \propto r^{-2}$ expectation of the adopted model, assuming mass traces light. In fact, the maximum optical depths for free-floating and bound planets are not very sensitive to the density profile. To first order, the fractions f_{bound} and f_{free} are inversely proportional to $\rho(r)$. Therefore, to first order, the dependence of the maximum optical depth on the density structure cancels out, and only the dependence of the velocity dispersion $\sigma(r)$ on the radius enters into the calculation of the maximum optical depth. Since this is a relatively insensitive function of the density structure, the maximum optical depths calculated previously are reasonably robust to variations in the space of realistic density models. I have also computed the optical depth for a Plummer model that has a density structure $\rho(r) \propto [1 + (r/r_c)^2]^{-5/2}$. This yields a total central optical depth almost identical to that for the fiducial model, $\tau \simeq 10^{-5}$. The maximum optical depths are $\tau_{\text{bound}}^{\text{max}} = 2.8 \times 10^{-7}$ and $\tau_{\text{free}}^{\text{max}} = 1.4 \times 10^{-7}$, about two times smaller than for the r^{-3} model, and 10 and 20 times smaller than inferred from the spike events. The true density profile is likely bracketed by the Plummer and r^{-3} models.

It should be emphasized that the procedure of setting $f_p = 1$ in the derivation of these maximum optical depths is not entirely self-consistent. The fractions f_{bound} and particularly f_{free} were derived under the assumption that the dynamics are dominated by the stellar component. If this is not the case, then both the encounter time t_{enc} and relaxation time t_{relax} may be considerably larger. Precise predictions of the behavior of the system in the presence of a substantial planetary component by mass would require a more sophisticated treatment than that presented here. Based on the determination of the mass-to-light ratio of M22, however, it is certainly true that the core of M22 cannot be currently be dominated by planetary-mass bodies. Therefore, the conclusions of §§ 4.1, 4.2, and 4.3 are secure: essentially regardless of its past dynamical evolution, a substantial population of planets cannot exist in the core of M22. As shown in Figure 3, within a projected radius of $1'$ from the cluster center, the halo contributes an optical depth of $\tau_{\text{halo}} = 3 \times 10^{-6}$ for the fiducial density model. This is also true for the Plummer model. Thus, reasonable models can reproduce the observed optical depth only if the entire halo is composed of planets. This is essentially excluded by measurements of the surface brightness (Trager et al. 1995) and mass-to-light ratio (Peterson & Cudworth 1994) of M22.

5. GALACTIC FREE-FLOATING PLANETS?

The results of § 4 strongly suggest that the spike events cannot be caused by microlensing by lenses associated with M22. Therefore, if one were to continue with the interpretation that these events are caused by microlensing, and assuming that the direction of M22 constitutes a generic

line of sight toward the Galactic bulge, the lenses constitute a free-floating Galactic population. What do the observations of SM22 imply about such a population under this assumption?

The optical depth inferred is independent of the location and nature of the lenses, therefore $\tau_{\text{spike}} = (2.9 \pm 1.2) \times 10^{-6}$ as before. The upper limit on the mass of the lenses is now less certain, but assuming the lenses have typical bulge distances and kinematics, I find $M_p \lesssim 0.5 M_J$ —still firmly in the planetary regime. The lower limit on the separation from the lack of detection of the primary is $a \gtrsim 6.3$ AU. Thus, the planets must still have relatively wide orbits to escape detection if they are bound to parent stars. The MACHO collaboration has measured the optical depth toward the Galactic bulge based on two different analysis methods. They find $\tau = (2.0 \pm 0.4) \times 10^{-6}$ centered at $(l, b) = (3^\circ 9, -3^\circ 8)$ using clump giants as sources (Popowski et al. 2001), and $\tau = (3.2 \pm 0.5) \times 10^{-6}$ centered at $(2^\circ 68, -3^\circ 35)$ using difference image analysis (Alcock et al. 2000). Note that these optical depths are *mutually exclusive* from that implied by the spike events, as the standard analysis techniques are not sensitive to events with timescales $\lesssim 1$ day. The optical depth is a relatively strong function of position. The models of Han & Gould (1995) indicate that the optical depth at the position of M22 should be 3–4 times smaller than the values measured at the positions reported by MACHO. These estimates are necessarily model dependent; however, for definiteness, I will assume that the optical depth toward the MACHO fields and Baade’s window, $(l = 1^\circ, b = -4^\circ)$, is 3 times larger than toward M22. Thus, the six spike events imply an additional optical depth of $\tau_{\text{BW}} = 3\tau_{\text{spike}} = 9 \times 10^{-6}$. Assuming that these planetary lenses have similar spatial and kinematic distributions as the bulge microlenses, this corresponds to more than $1800(M_p/0.5 M_J)^{-1}$ planets per bulge microlens.

These planets cannot be part of a halo population. The expected contribution to the optical depth toward M22 from a standard, spherical, singular, isothermal halo is (e.g., Sackett & Gould 1993)

$$\tau_{\text{halo}} = 5 \times 10^{-7} \left(\frac{v_\infty}{220 \text{ km s}^{-1}} \right)^2, \quad (33)$$

where v_∞ is the asymptotic halo circular speed. Introducing a core to the halo would decrease this estimate. Even if only one of the spike events was a result of microlensing by a halo object, this would imply an optical depth in planetary-mass objects toward the Large Magellanic Cloud in conflict with combined EROS and MACHO limits (Alcock et al. 1998).

These planets also cannot be part of the thin or thick disk. The optical depth to an exponential disk is (Gould, Miralda-Escudé, & Bahcall 1994)

$$\tau_{\text{disk}} = \frac{2\pi G \Sigma_d D_s^2}{hc^2} g(\alpha), \quad (34)$$

where Σ_d is the local surface density of the disk,

$$\alpha = D_s(|b|/h - 1/R_d), \quad (35)$$

$$g(\alpha) = \alpha^{-2} [1 - 2\alpha^{-1} + (1 + 2\alpha^{-1}) \exp(-\alpha)], \quad (36)$$

and h and R_d are the scale height and scale length of the disk, respectively. I adopt $R_d = 2.5$ kpc (see Sackett 1997 and references therein). The optical depth is maximized for

this value of R_d and the line of sight to M22 ($b = -7^\circ 6$) for $h = 0.6$ pc. The total observed surface density of matter is $40 M_\odot \text{ pc}^{-2}$ (Gould, Bahcall, & Flynn 1996; Zheng et al. 2001), while the surface density of all matter between ± 1.1 kpc and the plane is $71 M_\odot \text{ pc}^{-2}$ (Kuijken & Gilmore 1991), leaving room for an additional $31 M_\odot \text{ pc}^{-2}$ of dark matter between ± 1.1 kpc and the plane. This corresponds to $\Sigma_d = 37 M_\odot \text{ pc}^{-2}$, and thus the maximum optical depth toward M22 from a disklike component is $\tau_{\text{disk}} = 4.3 \times 10^{-7}$, about a factor of 7 smaller than that implied by the spike events.

Finally, Binney, Bissantz, & Gerhard (2000) argue that the optical depth to resolved events measured by MACHO toward the Galactic bulge using difference image photometry, $\tau = (3.2 \pm 0.5) \times 10^{-6}$, is *already* difficult to reconcile with our knowledge of Galactic structure (but see Sevenster & Kalnajs 2001). Thus, there is no room for the additional contribution of $\tau_{\text{BW}} \sim 9 \times 10^{-6}$, which would be required if the free-floating planets were smoothly distributed.

These arguments are, of course, indirect. There are several ways, however, of unambiguously detecting or ruling out such a free-floating planet population. The (unpublished) results of the MACHO spike analysis toward the Galactic bulge would likely answer this question definitively. Performing spike analyses on the OGLE-I or OGLE-II databases (Udalski et al. 1993, 2000; Udalski, Kubiak, & Szymanski 1997) might prove more difficult because of the lack of contemporaneous color information. During the OGLE-III phase, however, the sampling rates will be increased for some fields, enabling the resolution of considerably shorter timescale events. Finally, some events should be present in the databases of the follow-up microlensing collaborations. For example, the PLANET collaboration (Albrow et al. 1998) monitored $N_e \sim 60$ events toward the Galactic bulge with median sampling intervals of ~ 1 hr (Albrow et al. 2001; Gaudi et al. 2002), sufficient to resolve essentially all events caused by planets capable of producing the M22 spike events. The number of expected events in the PLANET database due to the implied free-floating planet population can be estimated roughly as

$$N_{\text{exp}} = \frac{2N_e \langle N_* \rangle \tau_{\text{BW}} \langle \Delta t \rangle}{\pi \langle t_E \rangle}, \quad (37)$$

where $\langle N_* \rangle \sim 10^3$ is the average number of additional stars on each frame, $\langle \Delta t \rangle \sim 40$ days is the average duration that each event was monitored, and $\langle t_E \rangle \lesssim 1$ day is the average planetary event timescale. Thus, $N_{\text{exp}} \gtrsim 15$ events should be present in the PLANET database if the implied population of Galactic free-floating planets is real.

All of these constraints can be avoided if the planets are not smoothly distributed. As suggested by de la Fuente Marcos & de la Fuente Marcos (2001), a dark cluster of planets along the line of sight toward M22 (but not associated with M22) could reproduce the observed spike events without violating any of the limits on Galactic structure. The minimum mass of the dark cluster required to reproduce the observed optical depth is

$$M_{\text{dc, min}} \simeq 7 \times 10^4 M_\odot \frac{x}{1-x}, \quad (38)$$

assuming the cluster radius subtends an angle ≥ 2.5 . Thus, unless the cluster is very close to us ($D_l \lesssim 1$ kpc), the dark

cluster must be quite massive, $M_{dc} \gtrsim 10^4 M_{\odot}$. See de la Fuente Marcos & de la Fuente Marcos (2001) for a more thorough discussion of the dark cluster interpretation.

6. DISCUSSION

The arguments of the previous sections lead to the conclusion that the only explanation for the origin of the spike events that is consistent with all available observations and theory is a dark, massive structure composed of light ($M \lesssim 1 M_{\odot}$) compact objects coincidentally along our line of sight to M22. Such an explanation seems ad hoc at best. The simplest alternative is that these events are not caused by microlensing. While it is not my intention to attempt to provide a definitive explanation for the spike events, in light of the evidence against the microlensing interpretation it seems worthwhile to review and reassess the reasons why SM22 favored the microlensing interpretation over other sources of variability.

The arguments in favor of the microlensing interpretation are that (1) the light curves are constant except for the spike event, (2) the colors and magnitudes of the sources are consistent with an unbiased sample of stars in the color-magnitude diagram (CMD), and (3) the distribution of magnifications is consistent with that expected from microlensing. The first reason is compelling, and rejects a large fraction of known variables. It is important, however, to note that the SM22 observations are restricted to 25 epochs over the course of 100 days, and thus only exclude variables with duty cycles $\gtrsim 4\%$. The fact that the distribution of source star magnitudes and colors is consistent with an unbiased sample of stars may not be very constraining because the number of proposed microlensing sources is quite small. Thus subtle biases are difficult to detect. Also, it is possible, perhaps likely, that low-mass main-sequence stars are those that are most likely to exhibit the required behavior: light curves that are constant to a few percent more than 96% of the time with brief brightenings of $\sim 50\%$ for less than 4% of the time. If this were the case one would naturally expect the distribution of such sources to roughly trace the CMD. Finally, the third argument, that the distribution of magnifications follows that expected from microlensing, is also not very constraining because of small number statistics. Figure 4 shows the cumulative distribution of $|\Delta m|$ for the six spike events. For microlensing, the cumulative distribution of magnifications normalized to $A = 1.34$ is simply $P(>A_T) = u_T^2$, where u_T is the radius of the $A = A_T$ magnification contour, and is given in equation (12) for point sources. The expected differential and cumulative distributions of $|\Delta m|$ for microlensing are shown in Figure 4. Also shown is a distribution that is uniform in $|\Delta m|$ over the observed range. Both distributions describe the data equally well.

At the distance to the Galactic bulge, and $E(B-V) = 0.33$, these sources are *brighter* than the theoretical main sequence (Girardi et al. 2000) by about 1 mag. They would lie on the main sequence if at ~ 5 kpc. Alternatively, the bulge stars could be significantly more reddened than assumed, $E(B-V) = 0.73$ versus $E(B-V) = 0.33$. Note that this would require a substantial amount of dust along our line of sight between M22 and the bulge. Without the original CMD, it is not possible to distinguish between these scenarios. However, given that SM22 conclude that the number distribution of these source follows the distribution of bulge sources, the latter scenario seems more likely.

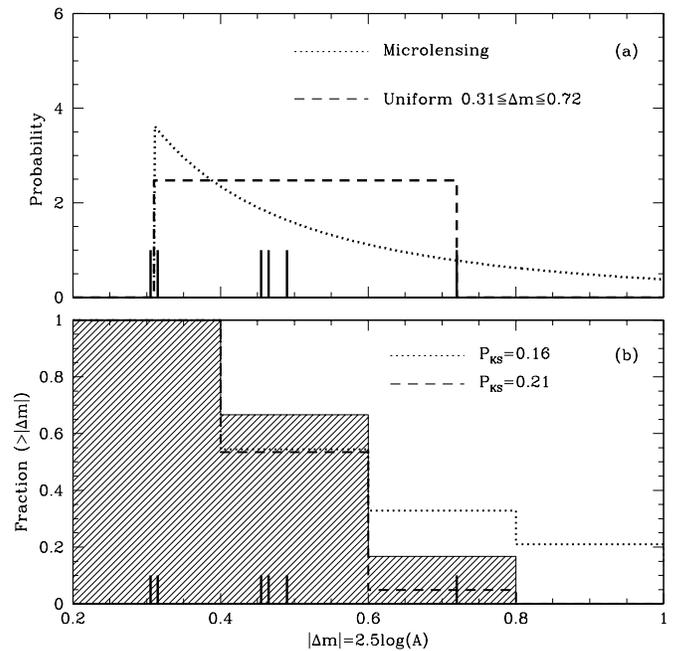


FIG. 4.—(a) Differential distributions of the magnitude difference $|\Delta m|$ for microlensing (dotted line) and a distribution that is uniform over the observed range of $|\Delta m|$ (dashed curve). The curves are arbitrarily normalized. The vertical segments are the observed $|\Delta m|$ for the six spike events. (b) The cumulative distributions of $|\Delta m|$, normalized to $|\Delta m| = 0.32$ (or $A = 1.34$). The shaded histogram is for the six observed events, the dotted histogram is the expected microlensing cumulative distribution, and the dashed histogram is for the uniform distribution. The Kolmogorov-Smirnov statistic probabilities are indicated.

If these sources are in fact above the bulge main sequence, it is possible that the sources are blends, e.g., M dwarf/white dwarf binaries. Such a scenario may be able to account for the color and magnitude of these sources and, furthermore, may explain the variability as well.

7. CONCLUSIONS

The primary conclusion of this study is that there is considerable circumstantial evidence that the six unresolved (spike) events detected by SM22 are not caused by microlensing, and therefore SM22 have not detected a substantial population of free-floating planets. The chain of logic is as follows:

1. Planetary-mass lenses bound to parent stars must be separated by $\gtrsim 8$ AU to explain the observations, or else the influence of the parent lens would have been detected.
2. In the core of M22, the encounter timescale is $t_{\text{enc}} \approx 4(a/\text{AU})^{-2}$ Gyr. Thus, all planets with separations $\gtrsim 0.6$ AU have been ionized by random stellar encounters over the lifetime of the cluster, $T_0 = 12$ Gyr.
3. The relaxation timescale in the core of M22 is $t_{\text{relax}} = 0.33$ Gyr. Thus, all free-floating planets have evaporated from the core.
4. For reasonable assumptions, the maximum possible optical depth to surviving planets in the halo of M22 falls considerably short of the observed optical depth of $\tau \sim 3 \times 10^{-6}$.
5. If smoothly distributed, the mass in free-floating Galactic planets required to produce the observed optical

depth is extremely difficult to reconcile with current knowledge of Galactic structure.

The only logical alternative is a dark cluster of planets with total mass $M \gtrsim 10^4 M_\odot$ that happens to be along our line of sight to M22. This explanation seems ad hoc at best.

Although there are no obvious alternative astrophysical candidates for these spike events, considering the weight of the arguments presented here, it would seem prudent to study existing data in order to fully characterize stellar variability at the relevant levels. Similar databases with higher temporal sampling, such as the *HST* time series photometry of the globular cluster 47 Tuc (Gilliland et al. 2000),

may be able to address this question definitively, without requiring additional resources.

I would like to thank Anthony Aguirre, Arlin Crotts, Xiaohui Fan, and Pawan Kumar for helpful discussions; John Bahcall for comments and encouragement; and Eugene Chiang, Andrew Gould, Ivan King, and an anonymous referee for comments and suggestions that led to an improved manuscript. This work was supported by NASA through a Hubble Fellowship grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

REFERENCES

- Albrow, M., et al. 1998, *ApJ*, 509, 687
 ———, 2001, *ApJ*, 556, L113
 Alcock, C., et al. 1998, *ApJ*, 499, L9
 ———, 2000, *ApJ*, 541, 734
 ———, 2001, *ApJ*, 552, 259
 Armitage, P. J. 2000, *A&A*, 362, 968
 Binney, J., Bissantz, N., & Gerhard, O. 2000, *ApJ*, 537, L99
 Binney, J., & Tremaine, S. 1987, *Galactic Dynamics* (Princeton: Princeton Univ. Press)
 Bonnell, I. A., Smith, K. W., Davies, M. B., & Horne, K. 2001, *MNRAS*, 322, 859
 Borucki, W. J., Koch, D. G., Dunham, E. W., & Jenkins, J. M. 1997, in *ASP Conf. Ser. 119, Planets beyond the Solar System and the Next Generation of Space Missions*, ed. D. R. Soderblom (San Francisco: ASP), 153
 Bouvier, J., Stauffer, J. R., Martin, E. L., Barrado y Navascués, D., Wallace, B., & Bejar, V. J. S. 1998, *A&A*, 336, 490
 Burgasser, A. J., et al. 1999, *ApJ*, 522, L65
 Chernoff, D. F., & Weinberg, M. D. 1990, *ApJ*, 351, 121
 Davidge, T. J., & Harris, W. E. 1996, *ApJ*, 462, 255
 Davies, M. B., & Sigurdsson, S. 2001, *MNRAS*, 324, 612
 de la Fuente Marcos, R., & de la Fuente Marcos, C. 2001, *A&A*, submitted (astro-ph/0108293)
 di Stefano, R., & Mao, S. 1996, *ApJ*, 457, 93
 di Stefano, R., & Scalzo, R. A. 1999a, *ApJ*, 512, 564
 ———, 1999b, *ApJ*, 512, 579
 Fabian, A. C., Pringle, J. E., & Rees, M. J. 1975, *MNRAS*, 172, 15P
 Fan, X., et al. 2000, *AJ*, 119, 928
 Gaudi, B. S. 2000, *ApJ*, 539, L59
 Gaudi, B. S., et al. 2002, *ApJ*, 566, 463
 Gaudi, B. S., & Gould, A. 1997, *ApJ*, 486, 85
 Gilliland, R. L., et al. 2000, *ApJ*, 545, L47
 Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, *A&AS*, 141, 371
 Gizis, J. E., Kirkpatrick, J. D., Burgasser, A., Reid, I. N., Monet, D. G., Liebert, J., & Wilson, J. C. 2001, *ApJ*, 551, L163
 Gonzalez, G. 1997, *MNRAS*, 285, 403
 Gould, A., Bahcall, J. N., & Flynn, C. 1996, *ApJ*, 465, 759
 Gould, A., & Loeb, A. 1992, *ApJ*, 396, 104
 Gould, A., Miralda-Escudé, J., & Bahcall, J. N. 1994, *ApJ*, 423, L105
 Hambly, N. C., Hodgkin, S. T., Cossburn, M. R., & Jameson, R. F. 1999, *MNRAS*, 303, 835
 Han, C. 1997a, *ApJ*, 484, 555
 ———, 1997b, *ApJ*, 490, 51
 Han, C., & Gould, A. 1995, *ApJ*, 449, 521
 ———, 1997, *ApJ*, 480, 196
 Heggie, D. C. 1975, *MNRAS*, 173, 729
 Hénon, M. 1961, *Ann. d'Astrophys.*, 24, 369
 Hut, P. 1983, *ApJ*, 268, 342
 Hut, P., & Bahcall, J. N. 1983, *ApJ*, 268, 319
 Jorissen, A., Mayor, M., & Udry, S. 2001, *A&A*, 379, 992
 Kirkpatrick, J. D., et al. 2000, *AJ*, 120, 447
 Kirkpatrick, J. D., Dahn, C. C., Monet, D. G., Reid, I. N., Gizis, J. E., Liebert, J., & Burgasser, A. J. 2001, *AJ*, 121, 3235
 Kuijken, K., & Gilmore, G. 1991, *ApJ*, 367, L9
 Lattanzi, M. G., Spagna, A., Sozzetti, A., & Casertano, S. 2000, *MNRAS*, 317, 211
 Laughlin, G. 2000, *ApJ*, 545, 1064
 Lee, H. M., & Ostriker, J. P. 1986, *ApJ*, 310, 176
 Lehnert, M. D., Bell, R. A., & Cohen, J. G. 1991, *ApJ*, 367, 514
 Mao, S., & Paczyński, B. 1991, *ApJ*, 374, L37
 Marcy, G. W., & Butler, R. P. 2000, *PASP*, 112, 137
 Marcy, G. W., Cochran, W. D., & Mayor, M. 2000, in *Protostars and Planets IV*, ed. V. Manning, A. Boss, & S. Russell (Tucson: Univ. Arizona Press), 1285
 Martín, E. L., Brandner, W., Bouvier, J., Luhman, K. L., Stauffer, J., Basri, G., Osorio, M. R. Z., & Barrado y Navascués, D. 2000, *ApJ*, 543, 299
 McCaughrean, M., et al. 2001, *Science*, 291, 1487
 Murray, N., Chaboyer, B., Arras, P., Hansen, B., & Noyes, R. W. 2001, *ApJ*, 555, 801
 Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, *Nature*, 378, 463
 Oppenheimer, B. R., Golimowski, D. A., Kulkarni, S. R., Matthews, K., Nakajima, T., Creech-Eakman, M., & Durrance, S. T. 2001, *AJ*, 121, 2189
 Paczyński, B. 1986, *ApJ*, 304, 1
 ———, 1994, *Acta Astron.*, 44, 235
 Paresce, F., & De Marchi, G. 2000, *ApJ*, 534, 870
 Peterson, C. J., & King, I. R. 1975, *AJ*, 80, 427
 Peterson, R. C., & Cudworth, K. M. 1994, *ApJ*, 420, 612
 Pinsonneault, M. H., DePoy, D. L., & Coffee, M. 2001, *ApJ*, 556, L59
 Piotto, G., & Zoccali, M. 1999, *A&A*, 345, 485
 Popowski, P., et al. 2001, in *ASP Conf. Ser. 239, Microlensing 2000: A New Era of Microlensing Astrophysics*, ed. J. W. Menzies (San Francisco: ASP)
 Press, W. H., & Teukolsky, S. A. 1977, *ApJ*, 213, 183
 Reid, I. N., et al. 1999, *ApJ*, 521, 613
 Sackett, P. D. 1997, *ApJ*, 483, 103
 Sackett, P. D., & Gould, A. 1993, *ApJ*, 419, 648
 Sahu, K. C., Casertano, S., Livio, M., Gilliland, R. L., Panagia, N., Albrow, M. D., & Potter, M. 2001, *Nature*, 411, 1022 (SM22)
 Santos, N. C., Israelian, G., & Mayor, M. 2001, *A&A*, 373, 1019
 Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
 Sevenster, M., & Kalnajs, A. 2001, *AJ*, 122, 885
 Smith, K. W., & Bonnell, I. A. 2001, *MNRAS*, 322, L1
 Spitzer, L. J. 1969, *ApJ*, 158, L139
 ———, 1987, *Dynamical Evolution of Globular Clusters* (Princeton: Princeton Univ. Press)
 Spitzer, L. J., & Thuan, T. X. 1972, *ApJ*, 175, 31
 Strauss, M. A., et al. 1999, *ApJ*, 522, L61
 Tabachnik, S., & Tremaine, S. 2001, *AJ*, submitted (astro-ph/0107482)
 Trager, S. C., King, I. R., & Djorgovski, S. 1995, *AJ*, 109, 218
 Udalski, A., Kubiak, M., & Szymanski, M. 1997, *Acta Astron.*, 47, 319
 Udalski, A., Szymanski, M., Kaluzny, J., Kubiak, M., Krzeminski, W., Mateo, M., Preston, G. W., & Paczyński, B. 1993, *Acta Astron.*, 43, 289
 Udalski, A., Zebun, K., Szymanski, M., Kubiak, M., Pietrzynski, G., Soszynski, I., & Wozniak, P. 2000, *Acta Astron.*, 50, 1
 Vesperini, E., & Heggie, D. C. 1997, *MNRAS*, 289, 898
 Witt, H. 1990, *A&A*, 236, 311
 Zapatero Osorio, M. R., Béjar, V. J. S., Martín, E. L., Rebolo, R., Barrado y Navascués, D., Bailer-Jones, C. A. L., & Mundt, R. 2000, *Science*, 290, 103
 Zheng, Z., Flynn, C., Gould, A., Bahcall, J. N., & Salim, S. 2001, *ApJ*, 555, 393