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ORBITAL IDENTIFICATION FOR ASTEROID 152563 (1992 BF) THROUGH THE YARKOVSKY EFFECT

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ABSTRACT

Often a newly discovered near-Earth asteroid is linked to old observations of a formerly lost object. This orbital identification is done using a standard dynamical model that accounts for gravitational perturbations from planets and relativistic effects. Here we report the first case where such an identification requires consideration of the Yarkovsky effect, a tiny non-gravitational perturbation due to the recoil of thermal radiation from the body. Moreover, this implies that the Yarkovsky force is revealed in the orbital motion of the body, asteroid 152563 (1992 BF), only the second case so far. Orbital fits indicate a drift in the orbital semi-major axis of $-(10.7 \pm 0.7) \times 10^{-4}$ AU Myr^{-1}, which we ascribe to Yarkovsky forces. This yields a correlated constraint of physical parameters such as the obliquity, rotation rate, surface thermal inertial, and bulk density. The magnitude and direction of drift point to an obliquity in excess of 120°. Observations taken during 2011 and subsequent close encounters with the Earth might help establish rotation parameters and thereby constrain thermal inertia of 1992 BF, thus making the Yarkovsky strength a measure of this asteroid's bulk density.

Key words: minor planets, asteroids

Online-only material: color figure

1. INTRODUCTION

Orbit determination for objects in the solar system is an old problem that has seen significant and innovative work in the past decade or so. Regarding the case of natural bodies, this is mainly because asteroid search programs have increased the number of known objects by orders of magnitude since the 1990s. This explosive growth has required an automated computational approach at all levels, and yet has also led to individual problems presented by peculiar asteroid cases. One particular aspect of the recent research has been to develop and optimize the process leading to identification of two sets of observations, distant in time, of a single object (e.g., Milani 1999; Milani et al. 2000, 2001; Bowell et al. 2002; Granvik & Muinonen 2005; Kubica et al. 2007). This is actually a frequent situation for both very small (thus faint) main belt asteroids and small and fast-moving near-Earth asteroids, whose early observations might cover a time of only less than a week (or even one or two nights). When the same object is later discovered, and observed enough in order to accurately determine its orbit, the question arises of whether the pre-discovery short-arc observations might be properly identified and used to reduce the orbit uncertainty. This type of identification is commonly referred to as an "attribution" of the isolated observations to the main arc of the orbit (e.g., Milani et al. 2001; Bowell et al. 2002).

Correct attributions often represent challenging problems because they depend on the accuracy of the orbit, its chaoticity, and the quality of the isolated observations (one of the most spectacular cases of successful attribution is that of 1937 UB Hermes; e.g., Skiff et al. 2003; Chesley & Chodas 2003). These are also the most frequent reasons for an attribution failure. Insufficiency of the dynamical model, used for the propagation of the orbit, is not yet a demonstrated case for such a failure. Still, with modern observations of small asteroids covering ever-lengthening time spans, it is reasonable to wonder whether this may occur, adding further complexity to the attribution process.

Indeed, several papers (e.g., Vokrouhlický et al. 2000, 2001; Vokrouhlický & Milani 2000; Vokrouhlický 2006) have argued that the recoil force due to thermal re-radiation of sunlight (the so-called Yarkovsky effect; see, e.g., Bottke et al. 2002) should be included in the force model to accurately predict the orbital position of several small near-Earth asteroids (NEAs) during their future close approaches to the Earth. This can be particularly important when accurate radar astrometry is available. Following the prediction by Vokrouhlický et al. (2000), Chesley et al. (2003) detected the effects of Yarkovsky forces using radar astrometry data from (6489) Golevka during its close approach to the Earth in 2003 May. Several other such cases are expected to occur in forthcoming years (e.g., Vokrouhlický et al. 2005a, 2005b), but to date none of them has provided an unambiguous detection of the Yarkovsky effect. Another aspect of the Yarkovsky force is its dependence on several *a priori* unconstrained parameters, such as spin state and surface thermal inertia. This produces a fundamental limitation on our ability to predict the future orbital position of these objects, including their possible impacts to planets. For instance Giorgini et al. (2002) demonstrated that the as-yet unconstrained Yarkovsky forces on 1950 DA produced by far the largest uncertainty regarding a possible Earth impact in 2880 March. Similarly, Chesley (2006) showed that these forces will soon prove important in predicting the trajectory of 99942 Apophis after its 2029 close approach to Earth.

While contributing to other aspects of orbital dynamics, the Yarkovsky forces have not so far proved to be necessary for successful attribution of past observations. Here we present the first such case. In particular, we note that the precovery observations of near-Earth asteroid 152563 (1992 BF) in 1953 January are displaced with respect to its orbit derived from its "nominal" set of observations spanning from 1992 to 2005. In Sections 3 and 4 we prove that this mismatch cannot be explained by inaccuracy of the 1953 observations. First, we carefully re-measure this asteroid position on precovery photographic plates and we also verify that no error in the time of observation can produce the observed displacement. From this point, we postulate that the mismatch is produced by incompleteness of the standard force model used for the attribution, namely by neglecting the thermal (Yarkovsky) forces acting on the asteroid. We then prove that the necessary strength of the thermal forces for linking the 1953 observations to the 1992 BF orbit is well within the expected range for a body of its size. The attribution effectively constrains the drift rate da/dt of the orbital semi-major axis a, which itself depends on several as-yet unknown physical parameters of this asteroid. Additional external constraints will help their decorrelation (discussed in Section 5). Interestingly, this is also the first time the Yarkovsky signal has been detected without the necessity of radar astrometry, relying thus on optical astrometry only. Future precise astrometry projects, both space-based, e.g., Gaia (Tanga et al. 2007) and ground-based, e.g., Pan-STARRS (Jedicke et al. 2007), and LSST (Ivezić et al. 2007), may also reveal many more cases such as 1992 BF.

2. 1992 BF: BASIC INFORMATION AND PRELIMINARY ESTIMATE OF THE YARKOVSKY-EFFECT STRENGTH

The small near-Earth asteroid 1992 BF was discovered on 1992 January 30 by Helin et al. (1992) as a part of the Palomar Planet Crossing Asteroid Survey using the 0.46 m Palomar Schmidt telescope. The available astrometric measurements basically cover this and subsequent close approaches of this object to the Earth, namely in 1992, 1997 and 2005, with a few observations also in 2003 December. In addition to this data set, four precovery observations have been associated with its orbit (Lowe 2002). These measurements were obtained from images taken during the nights of 1953 January 10 and 12 with the Palomar 1.2 m Schmidt. As described in detail below, the 1953 observations are discordant with predictions based on a purely gravitational force model. This prevents a simple orbital adjustment to link the 1953 observations with modern data.

Reported values of absolute magnitude for 1992 BF range between 19.5 and 19.8, with the most often seen value of 19.7. In this work we shall assume an albedo of $p_V = 0.15$, which leads to a diameter $D \simeq 400$ m, but if the true albedo is as low as 0.05 the size would recalibrate to 680 m. However, we consider this latter value unlikely (see, e.g., Delbò et al. 2003 or Binzel et al. 2004b for evidence of increasing albedo trend toward near-Earth asteroids of smaller sizes). Rotation period and pole position are currently unknown. 1992 BF has been classified as Xc type by Bus & Binzel (2002) (see also Binzel et al. 2004a, 2004b).

To preliminarily assess the expected strength of the Yarkovsky effect we note that near-Earth asteroids in the 1992 BF size range have surface thermal inertia values $\Gamma \sim 200$–800 J m^{-2} s$^{-1/2}$ K^{-1} (e.g., Delbò et al. 2007). If we take canonical values of the specific heat capacity $C_p \sim 600$ J kg^{-1} K^{-1} and surface-layer density $\rho_s \sim 2$ g cm^{-3}, we obtain a range of surface thermal conductivities: $K \sim 0.03$–0.5 W m^{-1} K^{-1}. At the mean orbital heliocentric distance of ∼0.9 AU and with typical rotation period $P \sim 4$ h, we obtain the diurnal thermal parameter $\Theta = \Gamma\sqrt{\omega}/(\epsilon\sigma T_\star^3) \sim 1$–$4$ with ω the rotation frequency, $\epsilon \sim 1$ the infrared emissivity, σ the Stefan–Boltzmann constant and $T_\star$ the sub-solar temperature (e.g., Vokrouhlický 1998, 1999; Vokrouhlický & Farinella 1998). This places the diurnal Yarkovsky component near its maximum efficiency, which generally dominates the seasonal component. As discussed in Vokrouhlický et al. (2000), the orbital position perturbation (including the sky-plane displacement) is dominated by the ability of the Yarkovsky forces to secularly change the semi-major axis a of the orbit. The linear heat diffusion theory for a spherical body yields (e.g., Vokrouhlický 1998, 1999)

$$\frac{da}{dt} \propto \frac{\cos\gamma}{\rho_b\, D}\, \frac{\Theta}{1+\Theta+0.5\,\Theta^2}\,, \qquad (1)$$

with γ being the obliquity of the spin axis and ρ_b the bulk density of the body. Thus the necessary sky-plane displacement to attain attribution of the 1953 January measurements, if truly due to the Yarkovsky forces, would constrain D, Θ, γ, and ρ_b in a correlated way as shown in Equation (1).

Our estimate for the maximum Yarkovsky drift rate for 1992 BF is $|(da/dt)_{\max}| \sim 1.4 \times 10^{-3}$ AU Myr^{-1} (this assumes $\gamma = 0^\circ$ or 180° and $\rho_b \sim 2.5$ g cm^{-3}). Using a simple estimate for the orbital longitude perturbation $\Delta\lambda$ given by Vokrouhlický et al. (2000), we find $\Delta\lambda$ might be as large as ∼4–5 arcsec back in 1953. Observations during a close approach to the Earth, such as in 1953 January, might find a Yarkovsky-induced sky-plane displacement of a factor of a few larger than $\Delta\lambda$. We may thus preliminarily conclude that the ∼6 arcsec disparity with respect to the nominal orbit prediction is not unreasonably large to be explained by Yarkovsky forces. Obviously, the proof must consist of detailed modeling of the relative orbit versus the observer geometry in 1953 January (Section 4).

3. REANALYSIS OF THE 1953 ASTROMETRY

Before the orbital displacement seen from the Palomar station in 1953 is attributed to Yarkovsky forces, we must first eliminate one obvious possible reason for the discrepancy, which is measurement error and uncertainty. Either the measurement of the object on the photographic plates or the recorded time might have been reported erroneously,[4] and this might confuse the attribution and potentially mask itself as the Yarkovsky-produced orbital displacement.

To remove any doubts about the quality of these past observations we have derived independent re-measurements of the asteroid trail ends witnessed on the digitized plates. Astrometric reductions were performed with the Astrometrica software package[5] and the USNO A2.0 star catalog. Subsequent re-reductions with the USNO B1.0 star catalog were not appreciably different. Our re-measurements were generally 2.5 arcsec south of those reported by Lowe (2002), who was the first to report the possible identification of the 1953 Palomar detections with 1992 BF. However, the better determined, and far more important, right ascension (R.A.) measures were substantially the same. Both sets of measurements are detailed in Table 1. Figure 1 depicts the trail of 1992 BF as it appears on the image of 1953 January 10.

The asteroid was moving predominantly southwards at the time of the 1953 images, leaving a trail 18 arcsec long in P.A. 186° on January 10 and 22 arcsec long in P.A. 189° on January 12 in the 10 min unfiltered exposures.[6] Because the trails are oriented predominantly north–south and locating the

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[4] Indeed, several other cases including 1999 LF6 or 2000 EE104 suggest this possibility for their single-night precovery observations.

[5] `http://www.astrometrica.at`

[6] The images were obtained using the USNO Integrated Image and Catalogue Archive Service `http://www.nofs.navy.mil/data/FchPix/cfra.html` (Levine & Monet 2000). The two plates we used are designated `1953-1-10 200__643_103a0` and `1953-1-12 200__651_103a0`.

Table 1
Prediscovery Measurements of 1992 BF (J2000.0 frame)

1953 Jan date	This paper		Lowe (2002)		Lowe offset	
	R.A.	Decl.	R.A.	Decl.	R.A.	Decl.
10.13681	03:55:01.60	+41°31′06.2″	03:55:01.60	+41°31′06.4″	+0.0″	+0.2″
10.14375	03:55:01.31	+41°30′44.6″	03:55:01.35	+41°30′47.1″	+0.4″	+2.5″
12.13681	03:54:28.50	+39°59′55.5″	03:54:28.53	+39°59′58.6″	+0.3″	+3.1″
12.14375	03:54:28.34	+39°59′38.0″	03:54:28.33	+39°59′40.7″	−0.1″	+2.7″

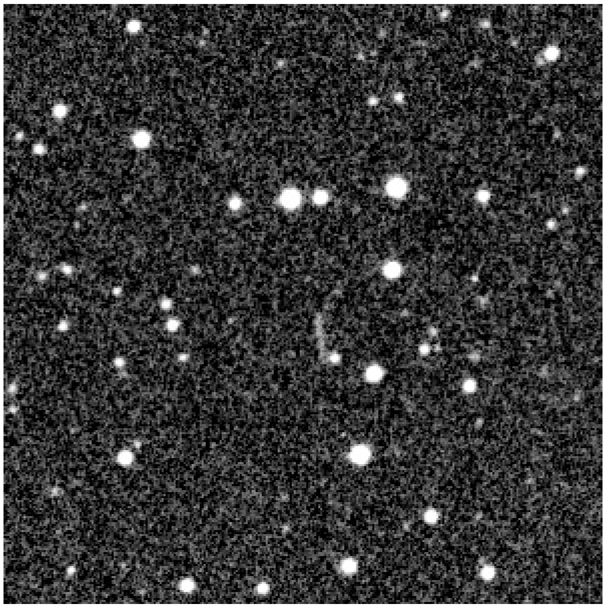

Figure 1. Image of the 1992 BF trail on the Palomar 1.2 m Schmidt image from 1953 January 10.

end points of the trail is much less precise than locating the trail centerline, the declination measurements are significantly less precise than those of the R.A. We judge the 1σ uncertainty of our measurements to be 0.5 and 1.0 arcsec in R.A. and declination, respectively.

The trail orientation and the associated measurement uncertainties are particularly favorable because, as will be described in more detail below, the apparent discrepancy between the measurements and the prediction is predominantly in R.A., which is determined with good precision. The relatively large uncertainty in declination (decl.) is actually compounded by the possibility of errors in the recorded observation time, but such errors cannot possibly account for the mismatch between the orbital prediction and the trail position.

4. ORBIT DETERMINATION

The process of fitting an orbit to a set of observations involves iteratively correcting the orbit of the asteroid until the trajectory best matches the observations. The best fit is the orbit that minimizes the sum of squares of the residuals, which are the difference between the measured and the computed sky positions, the latter determined according to the assumed orbital elements and dynamical model. Thus the residuals are the superposition of observational errors and orbital errors, and these two sources can be difficult to separate. However, when large residuals cannot be explained as measurement errors, as in this case, the residuals point to a model deficiency that must be resolved to obtain a reliable orbit.

The default dynamical model used for this object, and most other NEAs, includes gravitational perturbations from eight planets and the Moon, plus 1 Ceres, 2 Pallas, 4 Vesta, and 134340 Pluto. With an aphelion distance of 1.15 AU, well inside the orbit of Mars, the perturbations of other massive solar system objects will be insignificant. Relevant relativistic effects are also included. With this model, which neglects nongravitational accelerations, the predicted position of 1992 BF in 1953 January (plotted as squares in Figure 2) based on the 1992–2005 observation set is approximately 6 arcsec east of the observed trail (plotted as circles). The 1σ formal uncertainty in the prediction is only ± 0.2 arcsec in R.A. Not surprisingly, including these observations in the fit with the default model does not lead to acceptable post-fit residuals (triangles in Figure 2).

Extending the default dynamical model to include the Yarkovsky effect requires the assumption of several unknown parameters as outlined in Section 2, above. Additionally, the obliquity γ of the asteroid spin axis to its orbital plane must be assumed. Figure 3 depicts the dependence due to the Yarkovsky effect of the pre-fit and post-fit 1953 residuals upon the assumed obliquity, demonstrating that acceptable fits can be obtained for $\gamma > 120°$ and that values above 150° are preferred. The pre- and post-fit values obtained by neglecting Yarkovsky accelerations are similar to those plotted for $\gamma = 90°$.

Adopting $\gamma = 150°$ and fitting the asteroid bulk density along with a new orbit leads to normalized root-mean square (rms) of 1953 residuals of 1.04, very much in line with statistical norms. This orbital solution yields a bulk density $\rho = 2.5 \pm 0.2$ g cm^{-3} and a mean semi-major axis drift of $-(10.7 \pm 0.7) \times 10^{-4}$ AU Myr^{-1}, although it is worth noting here that such formal filter uncertainties are often optimistic by a factor of 2–3. The residuals from this fit are plotted as stars in Figure 2.

5. DISCUSSION AND CONCLUSIONS

The Yarkovsky-based attribution of the observations from 1953 January serves to constrain the value of the semi-major axis secular drift da/dt. At this moment, this leaves all other main physical parameters on which da/dt depends, namely size D, mean bulk density ρ_b, obliquity γ, and diurnal thermal parameter Θ, fully correlated. The last parameter further depends in a correlated way on the surface thermal inertia Γ and rotation period P, such that $\Gamma^2 \propto P$. Only some general conclusions can be given now, such that the negative value of da/dt requires $\gamma > 90°$, and its magnitude perhaps sets an even shaper constraint $\gamma > 120°$. Further independent observation will eventually decrease this degeneracy. To get a glimpse how this will help in understanding 1992 BF, we use results from the linearized heat diffusion theory for the secular drift of the orbital semi-major axis, namely Equation (1). Its value has been determined by the 1953 measurements attribution in Section 4. To break it into parametric dependences we shall

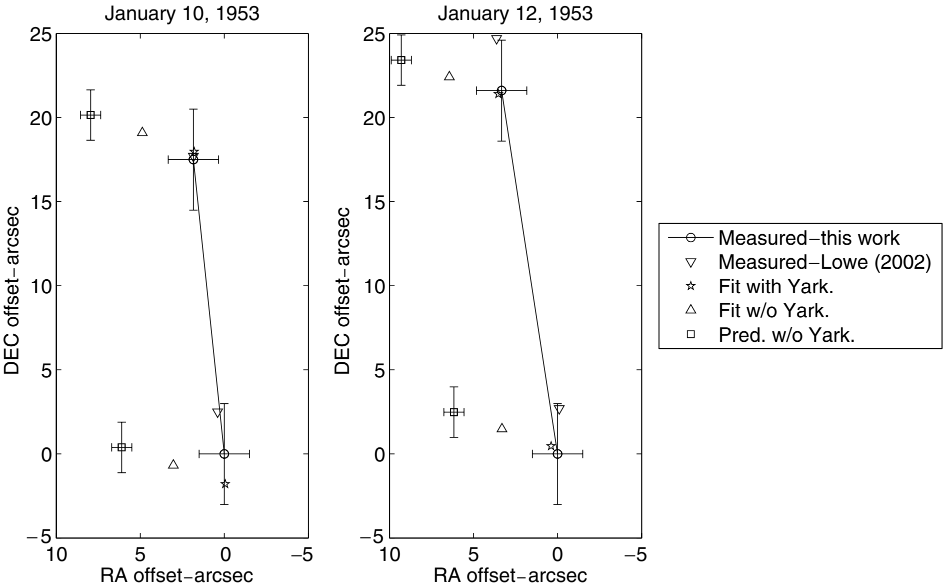

Figure 2. Measured and predicted positions of 1992 BF in 1953 January. The plotted line represents the asteroid trail on the two nights. Error bars represent 3σ uncertainty regions for the measured and the predicted positions. The origin is arbitrarily set to our measured end point of each trail.

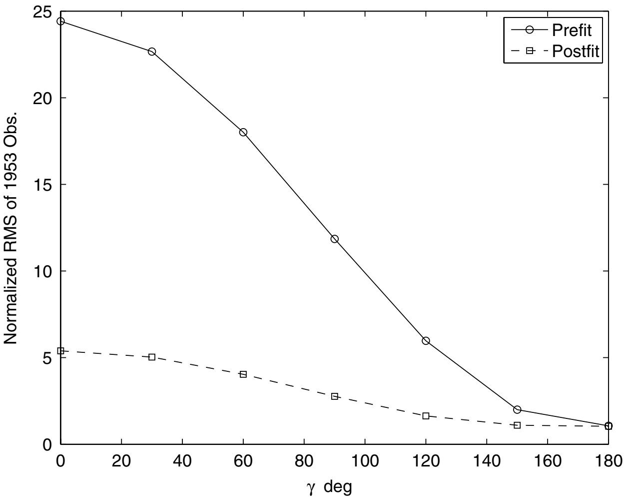

Figure 3. Dependence of normalized rms of 1953 residuals on assumed obliquity of the 1992 BF spin axis based on the linearized Yarkovsky model.

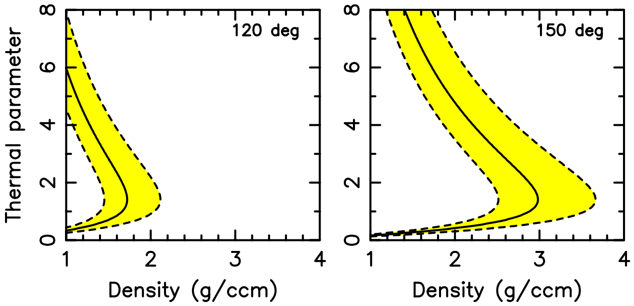

Figure 4. Admissible parameter solutions (gray region) for 1992 BF from detected Yarkovsky secular drift. The bold solid lines indicate the central solution and the 3σ extremes are denoted by dashed lines. The plot shows the parametric dependence on the bulk density ρ_b (the abscissa) and the thermal parameter Θ of the diurnal Yarkovsky effect (the ordinate). The left/right panels are for assumed obliquity $\gamma = 120°$, and $\gamma = 150°$, respectively. These solutions assume $D = 400$ m, but they simply recalibrate for other plausible D values through $\rho_b\, D =$ const relation. When future observations independently constrain γ, D and Θ, such as visible photometry and radiometry during the close Earth encounter in 2011, the Yarkovsky effect measurement will constrain the mean bulk density ρ_b.

(A color version of this figure is available in the online journal)

assume $D = 400$ m for the asteroid's size (note D occurs in da/dt only as $\rho_b D$ such that other D values would only rescale ρ_b values discussed below). Assuming different values of the the obliquity γ we may then indicate admissible solutions for ρ_b and Θ in the plane of these two parameters. Figure 4 shows this result for two values $\gamma = 120°$ (left) and $\gamma = 150°$ (right). As γ increases from about 120° the zone of admissible ρ_b and Θ parameters shifts toward larger ρ_b values, unless Θ is exceptionally small or large (for this reason an extreme obliquity value near $\gamma = 180°$ is unlikely). Note that the small or large Θ value might be a by-product of a very small or large value of the rotation period P, which itself might be set by the effect of radiation torques generically linked to the Yarkovsky effect. Indeed, the dynamically evolved orbit of 1992 BF may indicate that its spin state also approached an asymptotic state of the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) evolution with an obliquity value close to 180° and slow or fast rotation rate (e.g., Bottke et al. 2002). Future independent constraints of D, γ, and Θ should lead to a simple parametric dependence between the Yarkovsky da/dt value and ρ_b, allowing a robust determination of the bulk density of 1992 BF. This would be of particular interest since the bulk density of an Xc-type object has not yet been determined (e.g., Britt et al. 2002).

1992 BF experiences a distant close approach to the Earth in 2011 January, with a minimum distance of ∼0.18 AU and minimum V-band apparent magnitude ∼17.2. Unfortunately, radar imaging and astrometry cannot be used for 1992 BF in the foreseeable future. The asteroid can be sensed by the Arecibo system during a shallow close approach to the Earth in November 2016, but the signal-to-noise ratio for those echoes are estimated to be ∼40 only (assuming a canonical value of ∼4 h for the rotation period). While adding to the astrometry measurements of the orbit, these measurements perhaps do not have the power to significantly constrain the shape and rotation parameters of the body where it would be more needed. Observations at that time will have the power to (i) confirm and improve determination of the Yarkovsky effect in its orbital motion, and (ii) help constrain the physical parameters upon which the strength of the Yarkovsky effect depends. Additionally, photometric observations should resolve the rotation period of the body and set the stage for an eventual spin pole determination. Infrared observations could further constrain the body's size. As discussed above, this would direct the Yarkovsky-strength detection into a measurement of the body's mean bulk density.

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