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Letter to the Editor

The Carancas meteorite impact – Encounter with a monolithic meteoroid

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ABSTRACT

The formation of a 13-m wide impact crater by a stony meteorite near Carancas, Peru, on September 15, 2007 was an unexpected event. Stony meteoroids usually disintegrate in the atmosphere in many pieces, each landing at low velocity. We present examples of well-observed fireballs, which have all experienced atmospheric fragmentation. Using a simple model, we find that the Carancas meteoroid may have avoided fragmentation, if its strength was 20−40 MPa; such a strength would be comparable to the tensile strength of stony meteorites, but is higher than the strength of other observed meteoroids. We conclude that Carancas was a rare example of a monolithic meteoroid that was free of internal cracks. This example demonstrates that meteoroid strength can vary significantly from case to case and does not depend on meteoroid size. We estimate that the initial size of Carancas meteoroid was 0.9−1.7 m. Our model predicts an impact velocity that was in the range 2−4 km s^{-1}.

Key words. meteors, meteoroids – Earth

1. Introduction

The reports by the world media that a meteorite had struck the Earth and formed a 13-m wide crater in Peru on September 15, 2007 were initially met by skepticism in the scientific community. The reasons for this skepticism include the fact that it is common for people to associate erroneously a local event with a distant fireball seen low in the sky. This was the case, for example, for the "crater" reported in Honduras in 1996, which was in reality a landslide (Borovička et al. 1999). The formation of an impact crater on the surface of the Earth is also a rare event, presumably accompanied by an enormous fireball, as in the case of the Sikhote Alin iron meteorite fall in 1947 (Divari 1959). Today, enormous fireballs anywhere on the globe are easily detected by US Department of Defense satellites and the international network of infrasonic stations (see e.g. Klekociuk et al. 2005). The Peruvian event was not of an energy easily-detectable by these systems. Nevertheless, Peruvian scientists soon confirmed the impact nature of the crater (Macedo & Macharé 2007). They collected meteorite fragments found previously by local villagers. The meteorite proved to be an ordinary chondrite, which is a common type of stony meteorite. This fact was another large surprise. Small craters were believed to be formed only by iron meteorites, which are sufficiently strong to survive an atmospheric passage. In their review, Morrison et al. (2002) wrote: "the fortunate fact that the atmosphere protects us from impacting bodies smaller than a few tens of meters in diameter (except for the rare iron meteorites) has the consequence that we have almost no direct experience with cosmic impacts". This widely held belief was based on the observed fact that stony meteorites often hit the ground in showers of fragments (e.g. Jenniskens et al. 1994), video-observed meteorite falls show extensive atmospheric fragmentation (Brown et al. 1994; Borovička & Kalenda 2003), and detailed numerical modeling indicated that stony meteoroids always break-up in the atmosphere (Bland & Artiemeva 2006). In this paper, we discuss the Peruvian event in the context of data gathered from well-observed fireballs and perform simple modeling of the event.

2. Known facts

The Carancas meteorite fall occurred on September 15, 2007, at about 16:45 UT (close to local noon), in the densely-populated part of Andean altiplano near Lake Titicaca. A single crater of an average rim diameter of 13.5 m was formed at longitude 69°02′38″W, latitude 16°39′52″S, and altitude 3824 m (Macedo & Macharé 2007; Núñez del Prado et al. 2008; Rosales et al. 2008; Tancredi et al. 2008). Numerous small meteorites, mostly without fusion crust, were found in the vicinity of the crater and classified as ordinary chondrites H4-5 (Connolly 2008). The density of the meteorites was 3630 kg m^{-3} (Tancredi et al. 2008; Rosales et al. 2008).

Brown et al. (2008) identified signals associated with the meteorite fall in the records of infrasonic stations located in Bolivia (81 km from the crater) and Paraguay (1620 km). No signals were detected at more distant stations (>2200 km). The recorded signals were relatively weak, difficult to interpret, and indicated that the initial fireball energy was approximately 0.05 kT (1 kT TNT = 4.185 × 10^{12} J). From the entry modeling, Brown et al. (2008) concluded that the initial energy must have been in the range 0.1−0.3 kT to produce the observed crater.

The infrasonic data, combined with one seismic detection of the fireball and eyewitness reports, were used by Brown et al. (2008) to infer the fireball trajectory. The solution was not unique, but the preferred fireball radiant was positioned at azimuth 82° from the North and zenith distance z = 27°. In any case, the fireball arrived from the Eastern-Northeastern directions. Tancredi et al. (2008) computed the radiants of known

Table 1. Positions of fragmentations of well observed large European Network type I (chondritic) fireballs and the Morávka fireball.

EN fireball	E_∞	m_∞	m_E	M_{max}	v_∞	h_B	h_E	z	First fragm.		Main fragm.		Max. press.		Ref.
									h	p	h	p	h	p	
	T TNT	kg	kg		km/s	km	km	°	km	MPa	km	MPa	km	MPa	
EN070591	190	3500	10	−19.5	21.18	90.7	16.7	9.4	>50	<0.4	24	9	24	9	[2]
EN310800	2.8	100	5	−13.8	14.92	81.8	21.5	47.6	34	1.7	26	3.5	26	3.5	[1, 3]
EN171101	175	4300	450	−18.5	18.48	81.4	13.5	50.4	32	4	22	12	22	12	[1, 4]
EN060402[a]	16	300	20	−17.2	20.95	85.0	16.0	40.5	34	3.6	22	11	22	11	[1, 5]
EN231006A	10	100	0.2	−13.3	28.86	78.3	26.1	33.0	43	2.0	–	–	32	5.4	[1]
Morávka[b]	90	1500	100	−20.2	22.5		21.2	69.6	>46	<0.8	29	5.0	29	5.0	[6]

[a] Neuschwanstein meteorite fall (EL6 chondrite); [b] Morávka H5-6 chondrite fall.
Explanation of symbols: E_∞ – initial fireball energy; m_∞ – initial mass; m_E – total terminal mass expected to have fallen as meteorites (not recovered in most cases); M_{max} – maximum fireball absolute magnitude; v_∞ – initial velocity; h_B – fireball beginning height; h_E – fireball terminal height (end of ablation); z – zenith distance of radiant; h – height; p – dynamic pressure.
References: [1] this paper; [2] Borovička et al. (1998); [3] Spurný & Borovička (2001); [4] Spurný & Porubčan (2002); [5] Spurný et al. (2003); [6] Borovička & Kalenda (2003).

Near Earth Asteroids and concluded that the fireball radiant was probably located at low zenith distances ($z < 30°$). The equivalent argument would be that the helion source of sporadic meteors was located high in the sky at the time of fireball.

From the shape of the crater, Tancredi et al. (2008) estimated that the impact velocity was approximately 3 km s^{-1}. Harris et al. (2008) concluded, from the presence of planar microfabrics in some ejecta grains, that the meteoroid hit the ground largely intact and that the impact velocity could have been as high as 4–6 km s^{-1}. The fact that the eyewitnesses saw only one body and one impact (Macedo & Macharé 2007) and no meteorites were found far from the crater (although some may have fallen into the water) also suggests that the Carancas meteoroid did not experience significant atmospheric fragmentation.

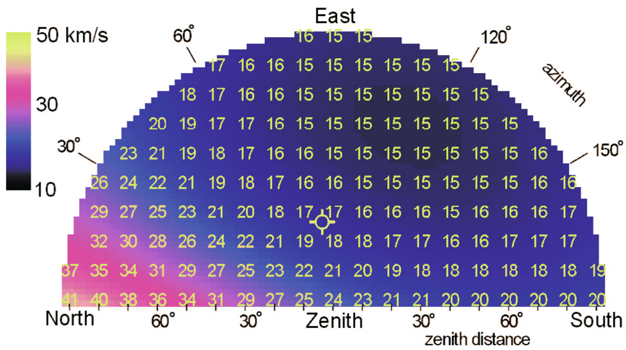

Fig. 1. The upper limit to the initial velocity as a function of radiant azimuth and zenith distance. Higher velocities would lead to Jupiter-crossing orbits. The plot is in polar coordinates. The cross indicates the nominal radiant of Brown et al. (2008).

3. Atmospheric fragmentation of meteoroids

The atmospheric fragmentation of meteoroids is a common phenomenon (e.g. Ceplecha et al. 1993). The process of fragmentation is not particularly well understood, but it is usually assumed that the fragmentation occurs when the dynamic pressure, $p = \rho_a v^2$, exceeds the bulk tensile strength of the meteoroid, where v is the meteoroid velocity and ρ_a is the atmospheric density. Some authors suggest that the pressure must be greater than the tensile strength to produce fragmentation (e.g. 2.7×, Nemtchinov & Popova 1997). The actual tensile strength was measured for a relatively small number of stone meteorite samples. The values, summarized e.g. by Svetsov et al. (1995), range from 2 to 62 MPa with a mean value of 29 MPa. However, meteoroids do fragment under much smaller dynamic pressures. In Table 1, we provide data on a sample of well-observed large fireballs from the European Fireball Network (see Spurný et al. 2007, for network description), which were certainly or likely to be caused by stony meteoroids. The sample includes meteoroids with various initial energies, masses, velocities, and trajectory slopes. All bodies experienced at least one significant episode of fragmentation. There is no obvious correlation of meteoroid strength with meteoroid mass or any other parameter. The three most-massive bodies behaved very differently – Morávka and EN070591 (Benešov) showed early disruption under a pressure much lower than 1 MPa, while EN171101 did not fragment until the pressure reached 4 MPa and its next fragmentation occurred only at 12 MPa. EN231006A fragmented at 2 MPa, but its daughter fragment survived 5.4 MPa without further fragmentation.

4. Modeling the Carancas fall

If the Carancas meteoroid did not fragment in the atmosphere, what was the magnitude of the dynamic pressure that it experienced? To answer this question, we modeled the Carancas fireball using the equations of flight for an ablating meteoroid traveling through the atmosphere (Ceplecha et al. 1998). A range of trajectory slopes, initial velocities, ablation coefficients, and drag coefficients was used. In each case, the initial meteoroid mass was adjusted to produce a prescribed impact velocity (i.e. the velocity at the height 3.8 km) in the range 2–6 km s^{-1}. The meteoroid was assumed to be spherical. The atmospheric density profile was taken from the MSIS-E-90 model (Hedin 1991)[1].

Since the meteoroid was an ordinary chondrite, its heliocentric orbit lay almost certainly inside the orbit of Jupiter. From that condition, the maximum possible preatmospheric velocity, v_∞, was computed as a function of radiant position. We considered radiants on the eastern half of the sky (Fig. 1). For the nominal radiant of Brown et al. (2008), the limiting velocity is 17.5 km s^{-1}. For radiants closer to the zenith or more to the North, the velocity could be higher. The high velocities at the northern radiant locations produce orbits with high inclinations (up to 70°), which are unlikely. From this consideration, we conclude that the initial velocity was probably lower than 18 km s^{-1} and almost certainly lower than 23 km s^{-1}.

The average ablation coefficient, σ, for type I fireballs is 0.014 s^2 km^{-2} (Ceplecha et al. 1998). This value, however,

[1] http://ccmc.gsfc.nasa.gov/modelweb/models/msis.html

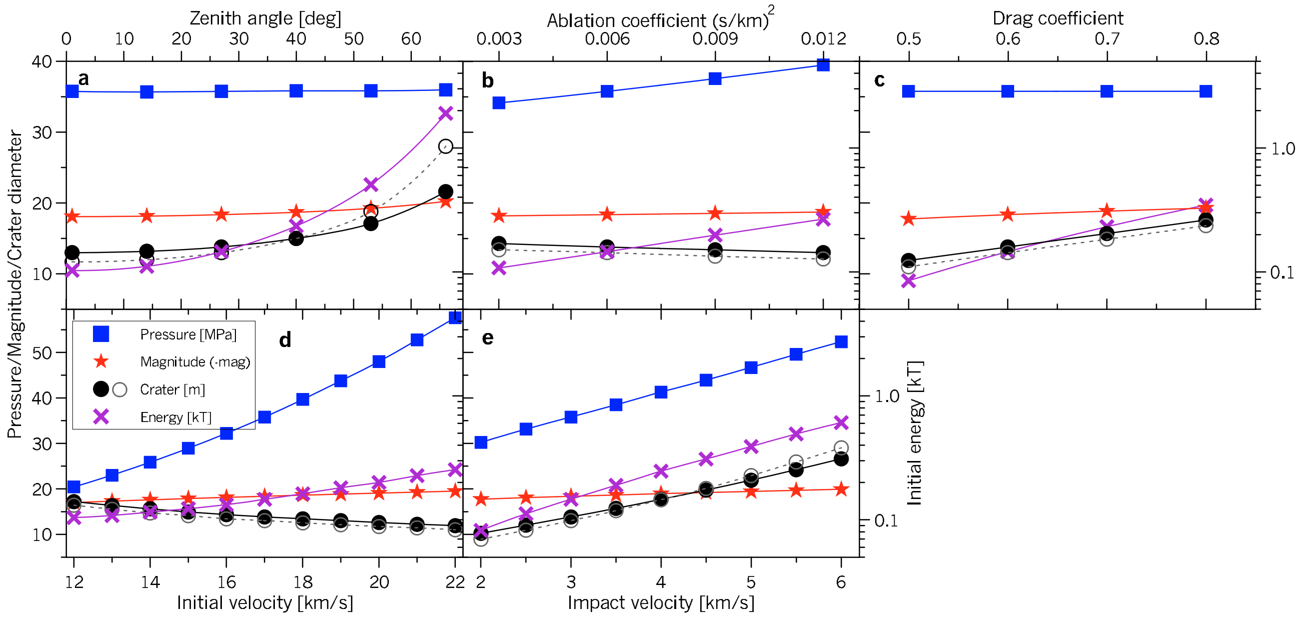

Fig. 2. Dependencies of maximal dynamic pressure in MPa (squares), maximal fireball absolute magnitude (negative sign omitted, stars), crater diameter according to Eq. (1) (filled circles) and Eq. (2) (empty circles), and initial fireball energy in kT (crosses, scale on the right) on the radiant zenith distance **a)**, ablation coefficient **b)**, drag coefficient **c)**, initial velocity **d)**, and impact velocity **e)**. In each plot, one parameter varies and the other four are kept at their nominal values. The nominal values of each parameter are $z = 27°$, $\sigma = 0.006$ s^2 km^{-2}, $\Gamma = 0.6$, $v_\infty = 17$ km s^{-1}, $v_{\rm imp} = 3$ km s^{-1}.

incorporates mass loss by fragmentation. Ceplecha & Revelle (2005) called it the apparent ablation coefficient. They found that the intrinsic ablation coefficient had a value between 0.004 and 0.008 s^2 km^{-2}. For most fragments of the Morávka fireball, it was found that $\sigma = 0.003$ s^2 km^{-2} (Borovička & Kalenda 2003). We considered the range 0.003–0.012 s^2 km^{-2}. For the drag coefficient, $\Gamma \equiv \frac{1}{2}C_{\rm D}$, we considered the range 0.5–0.8.

In each model, we computed the maximum fireball magnitude and the expected size of the crater. The absolute fireball magnitude is $M = -2.5\log(\tau\dot{E}/I_0)$, where $\dot{E}$ is the instantaneous loss of kinetic energy, $I_0 = 1500$ W (Ceplecha et al. 1998), and the luminous efficiency, τ, was computed according to the formula of Revelle & Ceplecha (2001). It reached about 10% close the fireball-brightness maximum. The crater diameter was computed according to the scaling law of Holsapple & Housen (2007),

$$D_{\rm crat} = 1.03\,D_{\rm imp}\left(\frac{\frac{1}{2}gD_{\rm imp}}{(v_{\rm imp}\cos z)^2}\right)^{-0.17}\left(\frac{\rho_{\rm g}}{\rho_{\rm m}}\right)^{0.332}, \qquad (1)$$

and also according to the formula given in Nemtchinov & Popova (1997),

$$D_{\rm crat} = 0.0133\,E_{\rm imp}^{0.29} + 1.51\,\rho_{\rm g}^{0.5}\rho_{\rm m}^{-0.5}D_{\rm imp} \quad \text{(in SI units)}, \qquad (2)$$

where $\rho_{\rm m}$, $v_{\rm imp}$, $D_{\rm imp}$, and $E_{\rm imp}$ are density, velocity, diameter, and energy of the impactor, respectively, g is gravity acceleration, $\rho_{\rm g}$ is density of the ground (assumed to be 2000 kg m^{-3}), and z is the zenith angle.

Figure 2a shows the dependence of the maximal dynamic pressure, $p_{\rm max}$, maximum fireball magnitude, $M_{\rm max}$, crater diameter, $D_{\rm crat}$, and initial fireball energy, E_∞, on the trajectory zenith angle, z, with the other free parameters (v_∞, $v_{\rm imp}$, σ, Γ) fixed. We see that $p_{\rm max}$ remains almost constant, but that zenith angles larger than ~35° require increasingly larger initial energies and produce larger craters. The reason is that shallow trajectories provide sufficient time for meteoroid deceleration. A large initial mass is therefore required to maintain the impact velocity. However, the ablation does not reduce significantly the mass and a large crater is formed.

Figure 2b shows that the dependence of the same parameters on the ablation coefficient is not very strong. Larger values of σ correspond to smaller crater sizes, but the initial mass must increase and $p_{\rm max}$ will also be larger. An increase in the drag coefficient must be compensated for by an increase in the meteoroid mass to maintain the required impact velocity. The crater dimensions and initial energy therefore increase with Γ (Fig. 2c). Nevertheless, deceleration does not change, $p_{\rm max}$ therefore remains exactly the same. Increasing the initial velocity produces a smaller crater (Fig. 2d), since a smaller initial mass is sufficient to reproduced the given impact velocity. The initial energy and, in particular, $p_{\rm max}$, however, increase. Finally, there is a steep increase in all parameters with the assumed impact velocity (Fig. 2e). The fireball magnitude increases with z, v_∞, $v_{\rm imp}$, Γ, and σ.

We consider acceptable solutions that provide a crater diameter, which is computed either according to Eqs. (1) or (2), in the range 12–15 m, and, at the same time, $p_{\rm max} < 40$ MPa, and $E_\infty < 0.3$ kT. Figure 3 shows, that for $\Gamma = 0.8$ only solutions with low impact velocities ($\lesssim$2.5 km s^{-1}) are possible. For $\Gamma = 0.5$, the value appropriate for a sphere moving in dense atmosphere, $v_{\rm imp} = 3.5$ km s^{-1}, or even 4 km s^{-1} for vertical trajectory, is possible in our model. The minimal possible fireball energy was about 0.05 kT and the corresponding dynamic pressure was at least 16 MPa and probably larger than 20 MPa. Assuming that $z < 30°$, the probable range of the initial meteoroid mass is 1500–10 000 kg (diameter 0.9–1.7 m), and the mass of the impactor was 900–4000 kg (diameter 0.8–1.3 m), which represents 18–82% of the original mass in the individual solutions. All solutions provide an initial velocity $\leq$20 km s^{-1}, maximum brightness of between −15.5 to −19.5 mag, and fireball duration (the part brighter than −10 mag) of 4–7 s. The maximum brightness always occurs at the height 16.5 ± 1 km and the maximal

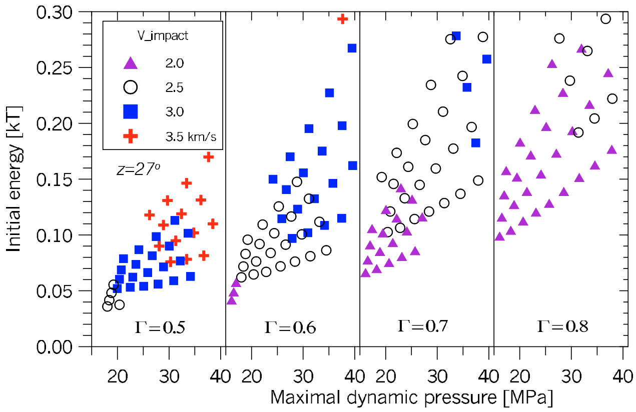

Fig. 3. The maximal dynamic pressure and initial energy for a range of acceptable solutions. Separate plots are given for each value of the drag coefficient Γ. Solutions with different impact velocities are indicated by different symbols: triangles for 2 km s^{-1}, circles for 2.5 km s^{-1}, squares for 3 km s^{-1}, and crosses for 3.5 km s^{-1}. For simplicity, only solutions for the zenith angle $z = 27°$ were included.

pressure occurs between 12 and 15 km. The projected velocity close to sea level (height 0.1 km) is only 0.5–1.7 km s^{-1}. Similar results were obtained by Brown et al. (2008).

5. Discussion

About 25 fireballs of 0.1 *kT* or higher fall annually to Earth (Brown et al. 2002). They rarely produce impact craters. Prior to the meteoric impact at Carancas, the last similar case was the Sterlitamak iron meteorite fall in 1990 (Petaev 1992). The majority of stony meteoroids fragment in the atmosphere under low dynamic pressure, probably because of the presence of internal cracks. The most important message from the Carancas event is that meteoroid strength is a unique property of each body and does not depend on size, as assumed in many models (Baldwin & Sheaffer 1971; Nemtchinov & Popova 1997; Bland & Artiemeva 2006). Ironically, the model of Hills & Goda (1993), who assumed the same strength for all bodies of the same type (50 MPa for hard stones) is applicable to Carancas. Carancas was a rare example of an homogeneous and monolithic meteoroid.

For crater formation to occur, it is not only important that the meteoroid strength be sufficiently high: the meteoroid size is also critically important. A larger meteoroid would not have slowed down sufficiently in the atmosphere (unless its trajectory was extremely shallow) and the dynamic pressure would eventually have exceeded the material strength. In the specific case of Carancas, the high altitude of the impact site was an additional advantage to the production of a crater.

Schultz et al. (2008) proposed that the Carancas meteoroid fragmented low in the atmosphere and that the fragment configuration reduced the deceleration. Such a scenario could lead to higher impact velocities than predicted in our model, but it contradicts our experience that fireball fragmentation leads always to increased deceleration and significant dispersion of the fragments (e.g. Borovička & Kalenda 2003). In any case, their scenario would not affect our conclusion on high meteoroid strength, since fragmentation would occur quite low in the atmosphere.

The meteorites recovered close to the crater were reported to be fragile (Núñez del Prado et al. 2008). The meteorites cannot be, however, considered to reflect the properties of the original meteoroid in this respect, since the material was subject to strong shock during the actual impact and may have been reduced almost to powder.

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References

Baldwin, B., & Sheaffer, Y. 1971, J. Geophys. Res., 76, 4653
Bland, P. A., & Artiemeva, N. A. 2006, Meteorit. & Planet. Sci., 41, 607
Borovička, J., & Kalenda, P. 2003, Meteorit. Planet. Sci., 38, 1023
Borovička, J., Popova, O. P., Nemtchinov, I. V., Spurný, P., & Ceplecha, Z. 1998, A&A, 334, 713
Borovička, J., Pineda de Carías, M. C., Ocampo, A., Tagliaferri, E., & Spalding, R. E. 1999, in Meteoroids 1998, ed. W. J. Baggaley, & V. Porubčan, Slovak Acad. Sci., Bratislava, 139
Brown, P., Ceplecha, Z., Hawkes, R. L., et al. 1994, Nature, 367, 624
Brown, P., Spalding, R. E., Revelle, D. O., Tagliaferri, E., & Worden, S. P. 2002, Nature, 420, 294
Brown, P., Revelle, D. O., Sukara, E. A., et al. 2008, J. Geophys. Res., submitted
Ceplecha, Z., & Revelle, D. O. 2005, Meteorit. & Planet. Sci., 40, 35
Ceplecha, Z., Spurný, P., Borovička, J., & Keclíková, J. 1993, A&A, 279, 615
Ceplecha, Z., Borovička, J., Elford, W. G., et al. 1998, Space Sci. Rev., 84, 327
Connolly, H. C. 2008, Meteoritical Bull., 93
Divari, N. B. 1959, in Sikhote-Alin Iron Meteorite Shower, Izd. Akad. Nauk, Moskva, 1, 26 (in Russian)
Harris, R. S., Schultz, P. H., Tancredi, G., & Ishitsuka, J. 2008, Lunar & Plan. Sci. Conf., 39, abstract # 2446
Hedin, A. E. 1991, J. Geophys. Res., 96, 1159
Hills, J. G., & Goda, M. P. 1993, AJ, 105, 1114
Holsapple, K. A., & Housen, K. R. 2007, Icarus, 187, 345
Jenniskens, P., Betlem, H., Betlem, J., et al. 1994, Meteoritics, 29, 246
Klekociuk, A. R., Brown, P. G., Pack, D. W., et al. 2005, Nature, 436, 1132
Macedo, L. F., & Macharé, J. O. 2007, The Carancas Meteorite Fall, Official INGEMMET initial report, released 21 September 2007
Morrison, D., Harris, A. W., Chapman, C. R., & Carusi, A. 2002, in Asteroids III, ed. W. F. Bottke Jr., et al. (Univ. Arizona Press), 739
Nemtchinov, I. V., & Popova, O. P. 1997, Astron. Vest., 31, 458 (Sol. Syst. Res., 41, 408)
Núñez del Prado, H., Macharé, J., Macedo, L., et al. 2008, Lunar & Plan. Sci. Conf., 39, abstract # 2555
Petaev, M. I. 1992, Astron. Vest., 26, 82 (Sol. Syst. Res., 26, 384)
Revelle, D. O., & Ceplecha, Z. 2001, in Proc. Meteoroids 2001 Conf., ed. B. Warmbein, ESA SP-495, 507
Rosales, D., Vidal, E., Ishitsuka, J., & Benavente, S. 2008, Lunar & Plan. Sci. Conf., 39, abstract # 1744
Schultz, P. H., Harris, R. S., Tancredi, G., & Ishitsuka, J. 2008, Lunar & Plan. Sci. Conf., 39, abstract # 2409
Spurný, P., & Borovička, J. 2001, in Proc. Meteoroids 2001 Conf., ed. B. Warmbein, ESA SP-495, 519
Spurný, P., & Porubčan, V. 2002, in Proc. ACM 2002, ed. B. Warmbein, ESA SP-500, 269
Spurný, P., Oberst, J., & Heinlein, D. 2003, Nature, 423, 151
Spurný, P., Borovička, J., & Shrbený, L. 2007, in Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, ed. G. B. Valsecchi, & D. Vokrouhlický, IAU Symp., 236, 121
Svetsov, V. V., Nemtchinov, I. V., & Teterev, A. V. 1995, Icarus, 116, 131
Tancredi, G., Ishitsuka, J., Rosales, D., et al. 2008, Lunar & Plan. Sci. Conf., 39, abstract # 1216