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The orbit and atmospheric trajectory of the Orgueil meteorite from historical records

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Abstract–Using visual observations that were reported 140 years ago in the *Comptes Rendus de l'Académie des Sciences de Paris*, we have determined the atmospheric trajectory and the orbit of the Orgueil meteorite, which fell May 14, 1864, near Montauban, France. Despite the intrinsic uncertainty of visual observations, we were able to calculate a reasonably precise atmospheric trajectory and a moderately precise orbit for the Orgueil meteoroid. The atmosphere entry point was ~70 km high and the meteoroid terminal point was ~20 km high. The calculated luminous path was ~150 km with an entry angle of 20°. These characteristics are broadly similar to that of other meteorites for which the trajectory is known. Five out of six orbital parameters for the Orgueil orbit are well constrained. In particular, the perihelion lies inside the Earth's orbit (q ~0.87 AU), as is expected for an Earth-crossing meteorite, and the orbital plane is close to the ecliptic (i ~0°). The aphelion distance (Q) depends critically on the pre-atmospheric velocity. From the calculated atmospheric path and the fireball duration, which was reported by seven witnesses, we have estimated the pre-atmospheric velocity to be larger than 17.8 km/sec, which corresponds to an aphelion distance Q larger than 5.2 AU, the semi-major axis of Jupiter orbit. These results suggest that Orgueil has an orbit similar to that of Jupiter-family comets (JFCs), although an Halley-type comet cannot be excluded. This is at odds with other meteorites that have an asteroidal origin, but it is compatible with 140 years of data-gathering that has established the very special nature of Orgueil compared to other meteorites. A cometary origin of the Orgueil meteorite does not contradict cosmochemistry data on CI1 chondrites. If CI1 chondrites originate from comets, it implies that comets are much more processed than previously thought and should contain secondary minerals. The forthcoming return of cometary samples by the Stardust mission will provide a unique opportunity to corroborate (or contradict) our hypothesis.

INTRODUCTION

It has been known that meteorites originate from outside the terrestrial atmosphere since the 1802 chemical analyses of Howard on eighteenth century falls (Marvin 1996), and the description of the 1803 l'Aigle fall by Biot (Gounelle, Forthcoming). Since then, much has been learned about the chemical and isotopic compositions, mineralogy, physical properties, and ages of meteorites (e.g., Kerridge and Matthews 1988). However, we have very little information on the parent bodies from which they originate.

Establishing a link between meteorites and their parent bodies is a key issue in planetary sciences because it bridges laboratory analyses of solid extraterrestrial samples with astronomical observations of celestial bodies. Some inferences about the origin of meteorites can be drawn by comparing their cosmochemical and physical properties to that of planetary bodies. The comparison of some meteorites with lunar rocks established with a high degree of certainty that 32 meteorites originated from the Moon (as of January 2005, including paired meteorites). A Martian origin has been attributed to 26 meteorites (as of January 2005, including paired meteorites) on the basis of the similarity in abundance and isotopic composition of trapped noble gases with that of the atmosphere of Mars (e.g., McSween and Treiman 2000). Though many matches between specific asteroid families and meteorite groups were tentatively established on the basis of infrared spectroscopy (e.g., Burbine et al. 2002), the only well-accepted association is that of asteroid 4 Vesta with howardite, eucrite, and diogenite (HED) meteorites (e.g., Binzel and Xu 1993). This is about all we can infer for the parent bodies of the 135 compositionally distinct meteorite groups (Meibom and Clark 1999) based on their cosmochemical and physical properties.

Another way to identify the origin of meteorites is to establish their orbit. Using this method, it is unlikely that we could pinpoint the exact parent body of a meteorite, but we can decisively identify from which region of the solar system it originated. Among the ~1050 meteorites whose falls have been witnessed (Grady 2000) since the first European recorded fall at Ensisheim in 1492 (Marvin 1992), an orbit has been determined for only a handful of them. Precise orbits for four meteorites were deduced from dedicated photographic programs: Příbram in Czechoslovakia in 1959 (Ceplecha 1961), Lost City in Oklahoma (USA) in 1970 (McCrosky 1971), Innisfree in Canada in 1977 (Halliday et al. 1978), and Neuschwanstein in Germany in 2002 (Spurný et al. 2003). Multiple video recordings by casual witnesses and satellite data helped determine the orbit of the Peekskill, Morávka, and Park Forest meteorites, which fell in 1992 in New York state (USA) (Brown et al. 1994), in the Czech Republic in 2000 (Borovička et al. 2003), and in Illinois (USA) in 2003 (Brown et al. 2004), respectively. Reasonably precise orbits were obtained for the Tagish Lake meteorite, which fell in Canada in 2000, by estimating from satellite fireball light curves and photographic/video records of the dust trail (Brown et al. 2000), as well as for the Saint Robert meteorite, which fell in Canada in 1994, by deducing from visual data and satellite observations (Brown et al. 1996).

Less precise orbits could also be deduced from visual observations for the Farmington (Kansas 1890 [Levin et al. 1976]), Abee (Canada 1952 [Griffin et al. 1992]), Vilna (Canada 1967 [Folinsbee et al. 1969]), Murchison (Australia 1969 [Halliday and McIntosh 1990]), Dhajala (India 1976 [Ballabh et al. 1978]), Omolon (Russia 1981 [Bronshten et al. 1999), Mbale (Uganda 1992 [Jenniskens et al. 1992]), and Pilia Kalan meteorites (India 1996 [Bhandari et al. 1998]). Research on that topic anterior to 1969 is reviewed in Millman (1969) and Levin and Simonenko (1969).

So far, all of the meteorites whose orbits are accurately known originate from the Asteroid Main Belt (Fig. 1). With the exception of Tagish Lake, all of them are high petrographic type chondrites (type 5 or 6), meaning that they have experienced significant thermal metamorphism on their parent body (van Schmus and Wood 1967). Tagish Lake is a low petrographic type meteorite (type 2) that has experienced extensive aqueous hydrothermal alteration on its parent body (Brown et al. 2000; Gounelle et al. 2001; Zolensky et al. 2002). In addition to these meteorites, it would be extremely valuable for planetary scientists to place some constraint on the orbit of certain key samples.

CI1 chondrites are extremely important and puzzling meteorites because, although heavily processed by low-temperature hydrothermal alteration (Bullock et al. 2005; Zolensky and McSween 1988), they are chemically pristine with a composition that is virtually identical to that of the solar photosphere (Anders and Grevesse 1989). Because of their very friable nature, CI1 chondrites cannot be preserved in the terrestrial environment (Gounelle and Zolensky 2001); all five known specimens are falls (Grady 2000). Among CI1 chondrites, Orgueil plays a special role since it is the most massive such fall, and has been the subject of extensive laboratory studies (e.g., Brearley and Jones 1998). The chemical composition of Orgueil is usually taken as the reference solar system average composition (Anders and Grevesse 1989).

The goal of this paper is to calculate the orbit of the Orgueil meteorite from historical records, namely, 140-year-old visual data. While working on another aspect of the Orgueil meteorite (Gounelle and Zolensky 2001), we noticed that decent descriptions of the fireball had been given at the epoch of the fall by numerous witnesses. The present paper is a summary of what could be deduced from the observations of those witnesses, who never could have guessed the importance of their enjoying a lovely spring evening outdoors in 1864.

THE FALL OF THE ORGUEIL METEORITE

The Orgueil meteorite fell in southern France near the city of Montauban (Tarn et Garonne) on May 14, 1864, shortly after 8 p.m. Immediately after the fall, a wealth of visual observations was diligently communicated to the Académie des Sciences; many were published by the most prominent mineralogist of the time, Auguste Daubrée (Daubrée 1864a, 1864b, 1864c).

The bolide associated with the fall of Orgueil was a spectacular event, sometimes described as being brighter and larger than the full Moon (see quote below). The fireball was seen as far away as the northern city of Gisors (600 km away from the meteorite fall). The most southerly reported observations were made in the coastal Spanish city of Santander (~400 km away from the meteorite fall). Sonic booms associated with the meteor were heard as far as 280 km away from the fall location (Fig. 2). Descriptions of the fall are often dramatic and poetic, as the following letter written by M. d'Esparbès at Saint-Clar (Gers) to Le Verrier[1] demonstrates (quoted by Daubrée (1864a).

> À 8 heures 13 minutes du soir, un effet de lumière prodigieux est venu inonder la ville. Chacun a cru se trouver au milieu des flammes. Cet effet a duré quelques secondes; il a été produit par quelque chose de la grosseur de la Lune au plein, qui s'est dirigé comme une étoile

[1]Urbain Le Verrier (1811–1877), a French astronomer best known for predicting the existence of Neptune using only celestial mechanics calculations.

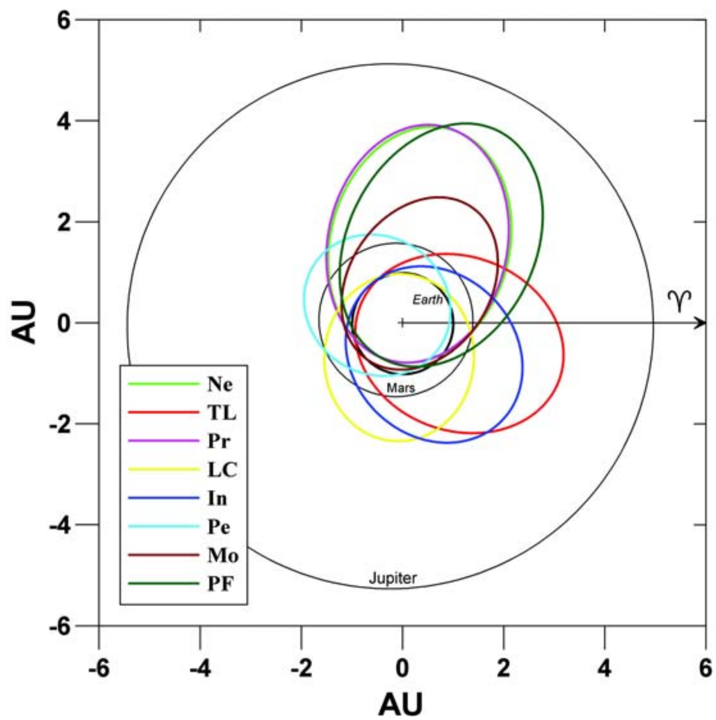

Fig. 1. Plot of the known meteorite orbits. Pr, LC, In, Pe, TL, Mo, Ne, PF stand for Příbram, Lost City, Innisfree, Peekskill, Tagish Lake, Morávka, Neuschwanstein, and Park Forest respectively. Data from Ceplecha (1961), McCrosky et al. (1971), Halliday et al. (1978), Brown et al. (1994), Brown et al. (2000), Borovička et al. (2003), Spurný et al. (2003), and Brown et al. (2004). γ gives the direction of the vernal point. The Earth, Mars, and Jupiter orbits are given for reference.

> filante, laissant à sa suite une traînée de feu légèrement bleuâtre. Cette traînée a disparu aussi peu à peu, et le ciel est redevenu serein; cependant, dix minutes après, ça produisait encore l'effet d'un long nuage fixe.
>
> Deux minutes environ après ce résultat de lumière électrique produit, une détonation comparable au bruit d'une pièce de canon, se prolongeant de quatre-vingts à cent secondes, s'est faite entendre.
>
> Il faisait une délicieuse soirée du mois de mai. Le temps était superbe.[2]

This description and others[3] correspond to what is usually reported by eyewitnesses who describe fireballs in modern times. The Peekskill (Brown et al. 1994), Lost City (McCrosky 1971), and Neuschwanstein (Oberst et al. 2004) fireballs have been reported to be brighter than the Moon. The Tagish Lake fireball was seen more than 700 km away from the meteorite fall location (Brown et al. 2002). The Saint Robert fireball was greyish blue (Brown et al. 1996), and the Neuschwanstein fireball had a deep blue or greenish head (Oberst et al. 2004). Sounds associated with the sonic boom produced by the supersonic flight of the meteoroid in the atmosphere are now compared to airplane booms, cannon noises, or prolonged thunder (Borovička et al. 2003). Sonic booms are usually heard more than 1 minute after the fireball identification (Borovička et al. 2003), as was the case for the Orgueil meteor. While for the Morávka meteor, sonic booms were heard only 100 km away from the place of fall (Borovička et al. 2003), they were heard several hundred km away for the Tagish Lake meteor (Brown et al. 2000).

Over sixty stones with a total weight approaching 15 kg were recovered soon after the event (Daubrée 1867). Searches were thoroughly conducted by local scientists and educated laymen, but also by peasants who could deal them at a good price (Daubrée 1867). This, according to Daubrée, warranted an efficient recovery of all the fallen samples. Despite the very fragile and incoherent nature of the Orgueil stone, which would prevent prolonged survival outdoors, the recovered 15 kg may be close to the total fallen mass (Daubrée 1867). Thirty-three stones were present in the collections of the Muséum d'Histoire Naturelle in 1867 (Daubrée 1867). This compares to 13 kg now present in the world collections (including samples present at the Musée de Montauban), and

[2]At 8:13 p.m., a prodigious luminous artifact inundated the city. Everyone thought to be in the middle of the flames. It lasted a few seconds and was generated by something as large as the full Moon that crossed the sky as a shooting star would, leaving a bluish fiery trail. This trail disappeared slowly, and the sky became serene again; however, ten minutes after, one could still observe an immobile cloud. Roughly two minutes after this electric light was produced, a detonation similar to that of a cannon, and lasting from 80 to 100 seconds was heard. It was a delightful May evening. The weather was superb.

[3]Because of the special nature of the basic data used in the present paper, we will be more than happy to communicate copies of all the nineteenth century papers we have in our possession that describe the fall of the Orgueil meteorite. These papers are in French.

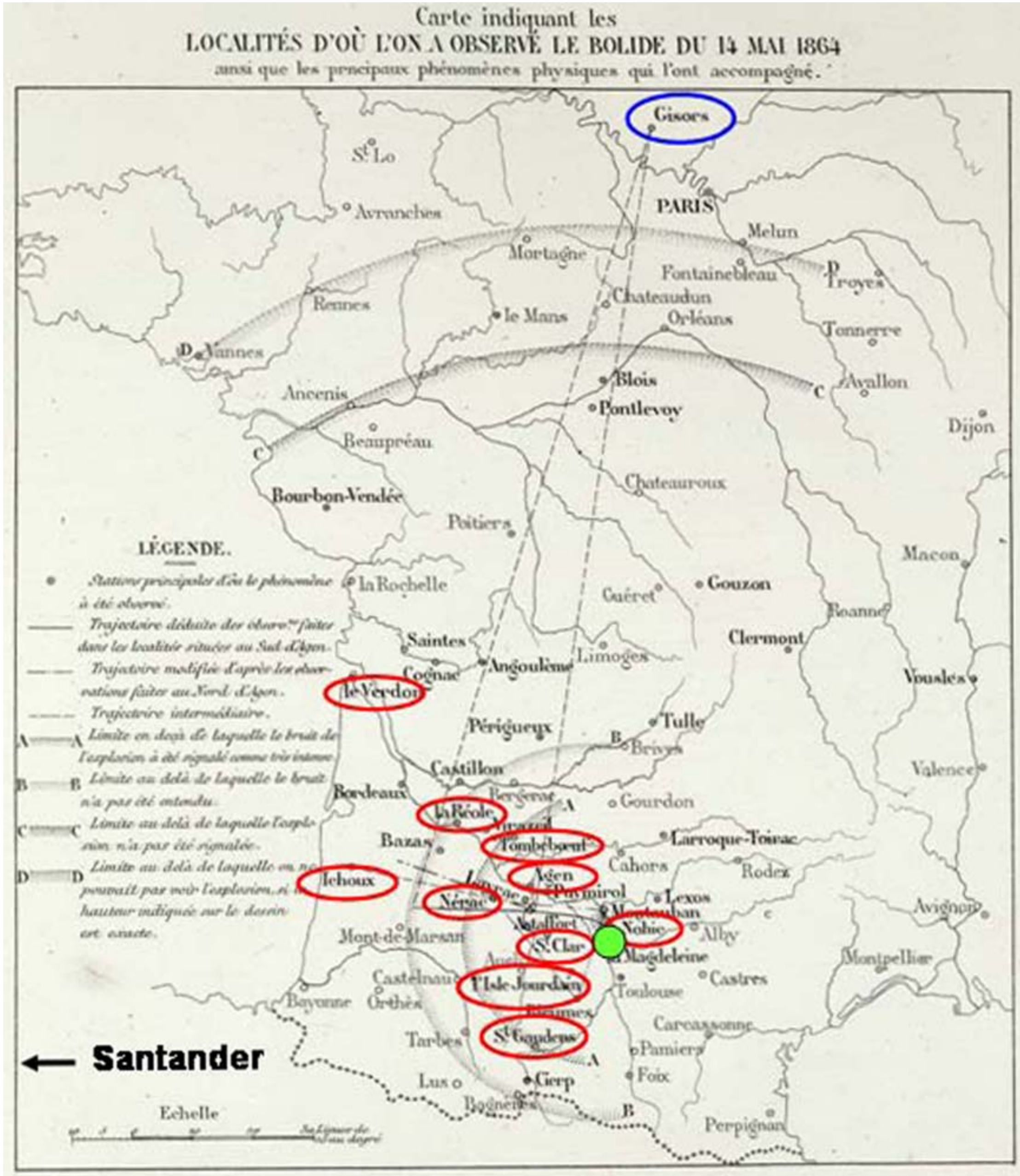

Fig. 2. Map indicating the locations from which the May 14 bolid was observed, together with the main associated physical phenomenona (Daubrée 1867). Places where phenomena were observed are marked with a dotted point. The AA line is the limit inside which the auditory phenomena were reported to be very intense. The BB line is the limit beyond which auditory phenomena were not reported. The CC line is the limit beyond which the visible fireball was not reported. The DD line is the calculated limit beyond which the visible fireball could not be seen. We have indicated the place of the fall by a green circle. The most septentrion observation has been circled in blue. Red circles underscore the location of the observations we took into account to calculate the trajectory and the orbit of the Orgueil meteor. The city of Santander (Spain) is off of the map. Scale is 1 cm equals 43 km.

23 samples recorded at the Muséum National d'Histoire Naturelle (Claude Perron, personal communication).

Stones were distributed along "a very extended oval" 20 km long and 4 km wide (Fig. 3) oriented from east to west, i.e., "approximately in the direction of the fireball movement" (Daubrée 1867). Most stones had an average weight of 100 g and were picked up close to the small town of Campsas. Smaller stones (minimum weight 15 g) were picked up in the western area, near the village of Montbéqui. All samples with masses larger than 1 kg were found in the western part of what is now known as a strewn field, with the most massive fragment (2 kg) found at the château de Beaudanger. Although Daubrée did not refer to it as a "strewn field," he gave the correct explanation for the most massive fragments

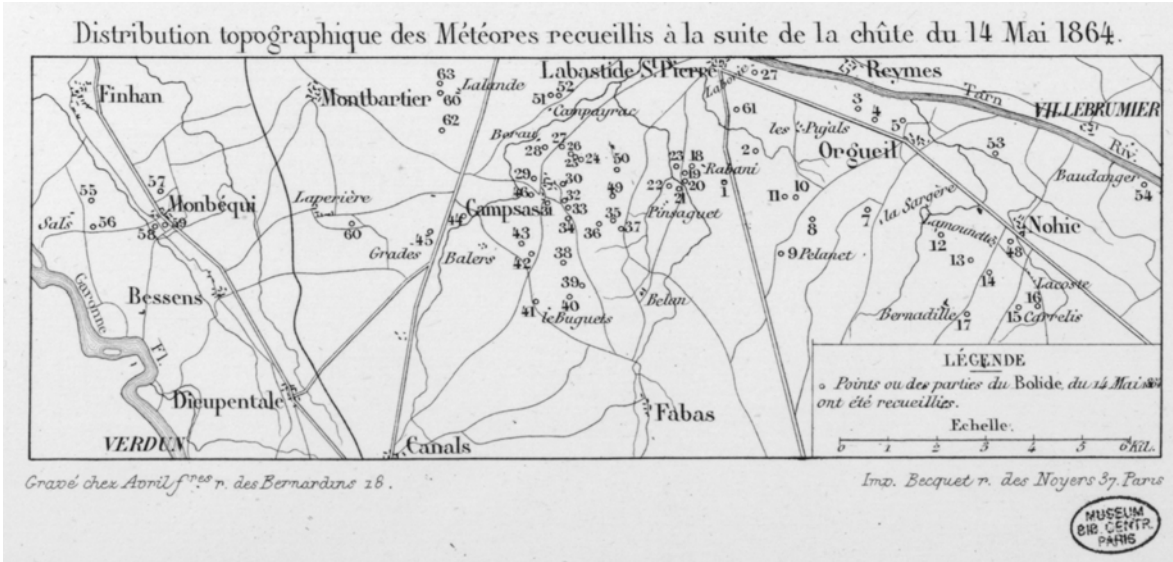

Fig. 3. Topographic distribution of the meteorites found following the fall of the May 14, 1864 bolide (Daubrée 1867). Note that there are more than 60 fragments. Daubrée (1867) mentions a catalogue that associated the fragment number with a mass, but we could not locate it. Scale is 1 cm equals 615 m.

travelling further away: “Ce triage a été évidemment produit par l’inégale résistance que l’air opposait à ces projectiles selon leur masse.”[4]

We have used the visual observations reported by Daubrée (1864a, 1864b, 1864c, 1867) to constrain the atmospheric trajectory and the orbit of the Orgueil meteorite 140 years after the fall. We specifically used the cross-checked examination of 13 reported fireball observations (Fig. 2; Table 1). We chose only those observations that could provide relevant and reliable information about the observed event. From our experience in interpreting eyewitness accounts of fireball events, we know that casual witnesses are unable to determine the exact position of the moving body on the sky. However, they can provide reliable information about trajectory attributes, such as if the bolide moved near the zenith from the left side to the right side, or in the opposite direction when it was observed; or if the bolide trajectory was below or above an important reference point on the sky (during the Orgueil flight, the Moon was near the first quarter, high in a clear sky, and visible over a large area of France). Another important and relatively reliable datum from more distant observers is whether the luminous path was rather horizontal or perpendicular to the horizon, and if the direction of the bolide flight near the horizon was from the left to the right or vice versa. We carefully collated all available historical sources and sorted those that provided information that fit the above-mentioned criteria. Surprisingly, our analysis of the eyewitness data produced a relatively consistent and reliable solution. This is also supported by the fact that, using a different method but with a similar set of observations, we independently obtained a similar solution for the atmospheric trajectory to that calculated 140 years ago (Laussedat 1864). The trajectory was determined using the method and software developed by Borovička (1990), while orbit was calculated following standard procedures described in Ceplecha (1987).

[4]This sorting was obviously produced by the different resistance offered by the air to stones of different masses.

THE ATMOSPHERIC TRAJECTORY OF THE ORGUEIL METEORITE

The apparent radiant position has a right ascension of 88.1 ± 0.4° and a declination of 27.6 ± 0.3°. The atmosphere entry point is estimated to be $H = 70 \pm 0.7$ km, $\lambda = 0.273 \pm 0.002$°W, and $\phi = 44.293 \pm 0.009$°N; the meteoroid terminal point is estimated to be $H = 19 \pm 0.6$ km, $\lambda = 1.339 \pm 0.001$°E, and $\phi = 43.891 \pm 0.007$°N, where λ, ϕ, and H are the longitude, latitude, and altitude above ground, respectively.

All values, according to their standard deviations, seem to be surprisingly precise, despite the fact that they are determined only from rough visual observations. However, we have to point out that this is the precision of the mathematical fit of the selected observations (Table 1). These error bars do not take into account the intrinsically imprecise nature of the visual data, which cannot be mathematically quantified (see the discussion about the selection of the data in the previous section). We expect that the reader will keep in mind that more realistic error bars are significantly larger than the quoted error bars.

The total luminous path, calculated from all of the visual observations that were used, is 150 ± 1 km. This very long observed trajectory derives from a combination of the fact that the initial Orgueil body was very large, with enough mass

Table 1. Visual observations of the fall of the Orgueil meteorite (May 14, 1864) selected to reconstruct the atmospheric trajectory and orbit of the meteorite (see text). A and Z stand for astronomical azimuth and zenith distance, respectively.

No.	Place of observation (observer)	Geographic coordinates	Original values	Corrected values (used in computations)	Comments
1.	Rieumes (Lajous)	λ = 1.118° E φ = 43.414° N	1. Point A = 156°, Z = 68° 2. Point A = 205°, Z = 73.5° (flare)	1. Point A = 156°, Z = 64° 2. Point A = 205°, Z = 74.5° (flare)	In the northern sky, from W to E Duration between both points 3 sec Loud sound after 3 min
2.	Nerac (Lespiault)	λ = 0.336° E φ = 44.138° N	1. A = 87.7°, Z = 52.6° (5° S from Pollux) 2. Several degrees N from zenith 3. A = 283°, Z = 39.5° (¼ distance between ε and α Boo from ε) 4. A = 300°, Z = 65° (flare 15° N from Jupiter)	1. Not used—too close to radiant 2. A = 180°, Z = 1°—rather almost zenith, slightly to N 3. A = 287°, Z = 39.5° 4. A = 288°, Z = 65°	Sound exactly 3 min after flare
3.	Montauban (Pauliet)	λ = 1.353° E φ = 44.019° N	1. SW 2. Constellation Leo ≈ A = 0°, Z = 30° 3. A = 324°, Z = 56° (left from Saturn and α Vir) 4. A = 307°, Z = 82° (slightly below Jupiter)	1. Not used 2. A = 0°, Z = 38° 3–4. Not used because these are beyond the impact area	Sound after 1–2 min
4.	Agen (Bourrieres)	λ = 0.625° E φ = 44.198° N	1. Over the town, somewhat to the S	1. A = 0°, Z = 18°	
5.	Layrac (Daubrée)	λ = 0.661° E φ = 44.133° N	1. Close to the zenith, literally flew overhead	1. A = 0°, Z = 10°	
6.	Astaffort (Lafitte)	λ = 0.650° E φ = 44.061° N	From NW to SE, very high—in zenith, terminated about 30° above SE horizon	1. A = 110°, Z = 20° 2. A = 0°, Z = 0° 3. A = 290°, Z = 45°	Observed just after 8:00 in the evening Sound after 4 min
7.	L'Isle Jourdain (Jacquot)	λ = 1.080° E φ = 43.613° N	Almost horizontal flight above northern horizon from W to E	1. A = 130°, Z = 62° 2. A = 205°, Z = 61°	Sound after 3–4 min; exploded and fragmented into many pieces; persistent train 15 min
8.	Ichoux (newspaper)	λ = 0.968° W φ = 44.328° N	Almost perpendicularly to the horizon, direction from west to east	1. A = 277°, Z = 45° 2. A = 284°, Z = 83°	Around 8:00 in the evening; duration several seconds; 3 detonations
9.	Verdon (Laussedat)	λ = 0.628° E φ = 44.814° N	1. A = 29.5°, Z = 43.6°—across the Moon	1. A = 29.5°, Z = 54°	
10.	La Reole (Laussedat)	λ = 0.036° W φ = 44.588° N	1. A = 29.6°, Z = 44.4° (Moon position) above or across the Moon	1. A = 30°, Z = 30° shifted about 14° above the Moon—in agreement with observation	
11.	Bezu-Saint-Eloi (Brongniart)	λ = 1.695° E φ = 49.296° N	On southern horizon, somewhat to the west, near horizon (~10–15°), slope to the horizon about 20–25°	1. A = 15°, Z = 86° 2. A = 9°, Z = 88° Must be much closer to horizon	Between 7:50 and 8:00 in the evening
12.	Tombeboeuf (Cruzel)	λ = 0.455° E φ = 44.508° N	WNW→above Leo→left from Saturn and αVir 1. Point A = 49°, Z = 20° (above Leo) 2. Point A = 330° = 55° (flare, between Saturn and α Vir) 3. Point A = 307°, Z = 82° (end near to Jupiter)	1. Point A = 49°, Z = 38° 2. Point A = 338°, Z = 55° 3. Point A = 312°, Z = 82°	Sound 2.5 min after
13.	Orgueil (meteorite position)	λ = 1.400° E φ = 43.875° N	1. A = 0°, Z = 0° (in zenith)	1. A = 110°, Z = 1° (in zenith)	Impact place

Table 2. Properties of the atmospheric trajectory of Orgueil compared to that of other meteorites. Pr, LC, In, Pe, TL, Mo, Ne, PF stand for Příbram, Lost City, Innisfree, Peekskill, Tagish Lake, Morávka, Neuschwanstein, and Park Forest, respectively.

	Pr	LC	In	Pe	TL	Mo	Ne	PF	Orgueil
Initial velocity (km/sec)	20.9	14.1	14.5	14.7	15.8	22.5	20.9	19.5	>17.8
Beginning height (km)	98	86	62[a]	60	66	80[b]	85	82	70
Terminal height (km)	13[b]	19	20	34	29	21	16	18	19
Duration (s)	6.8	9	4.1	>40	?	9	5.3	4.3	<10
Trajectory slope[c] (°)	43	38	68	3	18	20	49	61	20
Atmospheric path (km)	125	109	46	>700	120	163[b]	91	73	150

[a]Fireball beginning was captured only on low quality photo from large distance.
[b]Taking visual data into account.
[c]The trajectory slope is relative to the horizontal.

Table 3. Orbital elements of the calculated Orgueil orbit as a function of the entry velocity ν. a is the semimajor axis, e the eccentricity, q the perihelion distance, Q the aphelion distance, ω the argument of perihelion, Ω the longitude of the ascending node, and t_p the date of the perihelion passage.

	ν = 16 km/sec	ν = 17 km/sec	ν = 18 km/sec	ν = 19 km/sec	ν = 20 km/sec
a (AU)	2	2.5	3.3	4.7	8
e	0.57	0.65	0.73	0.82	0.9
q (AU)	0.88	0.87	0.87	0.87	0.86
Q (AU)	3.2	4.1	5.7	8.5	16
ω (°)	310	311	312	313	233
Ω (°)	234	234	233.9	233.5	55
i (°)	0.9	0.6	0.3	0.1	0.1
t_p (days after fall)	37	35	33	32	31

to allow for extensive ablation, but survival of fragile kg-size stones at the surface; and also by the fact that the trajectory was relatively shallow with a slope relative to the horizontal of only 20 ± 0.4°. This low inclination trajectory is in good agreement with the dimension of the area over which meteorites were recovered (Fig. 3). Similarly, a large impact area was observed for the videotaped Morávka meteorite fall (Borovička et al. 2003), where the slope of atmospheric flight to the horizontal was also 20°.

Our calculated atmospheric trajectory (Fig. 4) is similar to that determined by Laussedat (1864) within weeks following the fall (Fig. 5). This is not surprising, since Laussedat worked on the same data set, and, as geodesy professor at the École Polytechnique (1856–1871) and later as head of the Conservatoire des Arts et Métiers (1881), was an expert in triangulation calculations. The characteristics of the Orgueil atmospheric trajectory are within the range observed for other meteorites (Table 2). When compared to Tagish Lake, which is most similar chemically and petrographically to Orgueil (Brown et al. 2000; Gounelle et al. 2001; Zolensky et al. 2002), the only noticeable difference is the deeper penetration of Orgueil within the atmosphere. Because the penetration in the atmosphere depends on a range of poorly known parameters (pre-atmospheric size, porosity, initial velocity, density, and so forth), it is difficult to retrieve any valuable information from that observation.

THE ORBIT OF THE ORGUEIL METEORITE

The orbit of any celestial body is fully determined by six independent parameters: the argument of perihelion (ω), the longitude of the ascending node (Ω), the inclination (i), the time of perihelion passage (t_p), the perihelion distance (q) and the aphelion distance (Q). As for the Morávka and Park Forest falls, the fireball pre-atmospheric velocity is a key parameter in determining the orbital parameters (Borovička et al. 2003; Brown et al. 2004). Five orbital parameters (ω, Ω, i, t_p, and q) are quite well-constrained by the visual observations, and are almost independent of the fireball pre-atmospheric velocity (Figs. 6a and 6b; Table 3).

In contrast, the elements describing the size of the orbit, such as the semimajor axis, the eccentricity, or the aphelion distance, depend strongly on the meteor's pre-atmospheric velocity, ν (Figs 6c and 6d; Table 3). In particular, our analysis has identified a boundary pre-atmospheric velocity (ν_J = 17.8 km/sec, where J stands for Jupiter). If the fireball pre-atmospheric velocity is larger than ν_J = 17.8 km/sec, the Orgueil meteoroid aphelion (Q) is larger than Jupiter's semi-major axis (a_J = 5.2 AU) (Fig. 6c).

The bolide average atmospheric velocity is $\nu = D/t$, where D is the length of the atmospheric path and t the duration of the fireball. Because the bolide decelerates in the atmosphere, the pre-atmospheric velocity is significantly

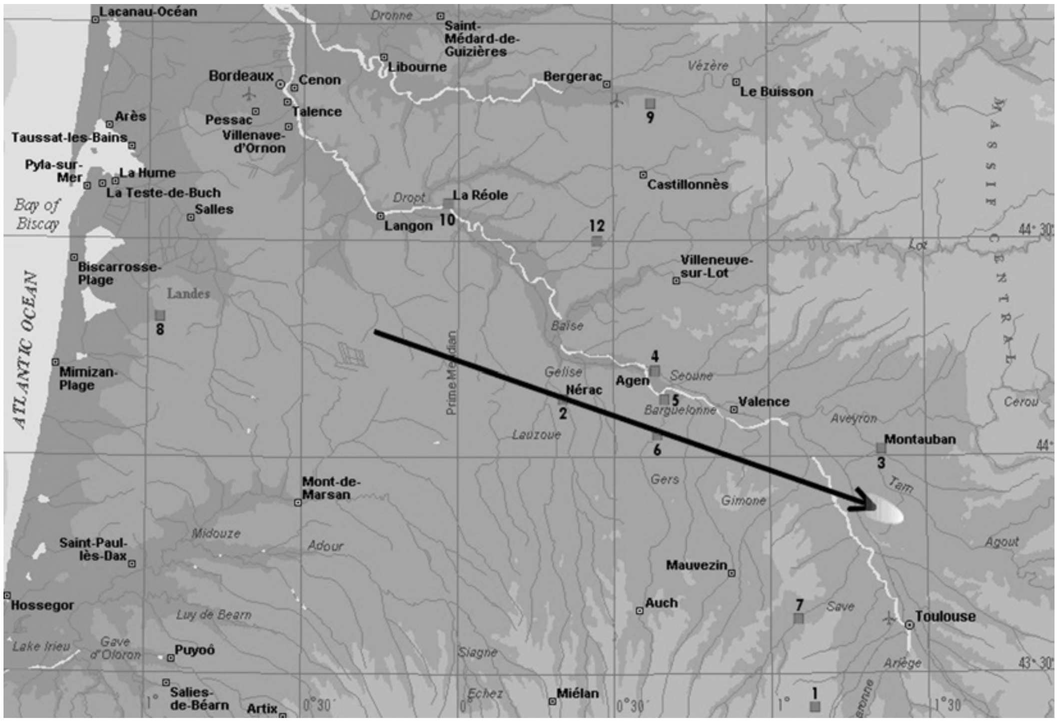

Fig. 4. The calculated trajectory of the Orgueil meteor (this work). The numbered squares show the location of the observations we took into account in calculating the trajectory and the orbit of the Orgueil meteor (numbers refer to Table 1). Using the same projection, the trajectory calculated by Laussedat (1864) would be indistinguishable from the one we calculated. Scale is 1 cm equals 12.3 km.

higher than the average atmospheric velocity. The discrepancy between pre-atmospheric and average atmospheric velocity has been estimated for all the meteoroids detected by the European Network (EN) that have a significant terminal mass, in most cases larger than 1 kg, to be ν/v =1.22 (Table 4). If we restrict ourselves to the meteorites that have been observed to fall, i.e. Příbram, Lost City, Innisfree, Morávka, Neuschwanstein, and Park Forest, we calculate that ν/v varies from 1.13 to 1.29 with an average value of 1.20, where the average velocity is the atmospheric path divided by the fireball duration. We will adopt here the value $\nu/v = 1.20$. Note that although this formula depends on many aspects of the meteoroid flight in the atmosphere, it provides a good empirical description of large meteoroids producing meteorite falls. It is also worth mentioning that, since the physical properties of the Orgueil meteorite are different than any other meteorite, the adopted ν/v is a best guess using our incomplete knowledge.

We therefore have $\nu = 1.20 * v = 1.20 * D/t$ where ν and v denote the pre-atmospheric and atmospheric velocity, respectively. The boundary atmospheric velocity is $v_J = 17.8/1.20 = 14.8$ km/sec. Since the atmospheric path is ~150 km, an atmospheric velocity of $v_J = 14.8$ km/sec corresponds to a fireball duration of ~10 sec. If the fireball duration is smaller than 10 sec, the Orgueil fireball aphelion is outside the orbit of Jupiter; if greater than 10 sec, the Orgueil aphelion is inside the orbit of Jupiter. Fortunately, as many as seven observers reported the fireball duration:

Le temps pendant lequel le bolide a parcouru la distance des deux points observés a été évalué à 3 secondes.[5] (M. Lajous, in Daubrée [1864c], p. 1067.)

La durée de son apparition a été tout au plus de quelques secondes, et après sa disparition on ne tarda pas à entendre une forte detonation.[6] (M. de Saint Amans, in Daubrée [1864c], p. 1069).

Son diamètre apparent était celui de la pleine Lune, sa vitesse était moindre que celle d'une étoile filante: toutefois la durée de son apparition ne fut pas plus de cinq à six secondes.[7] (M. Laurentie, in Daubrée [1864c], p. 1069).

La durée du phénomène a été de quelques secondes.[8] (Anonymous, quote from a Perigueux newspaper, in Daubrée [1864c], p. 1070).

La durée du phénomène fut de quelques secondes.[9] (M. Triger, in Daubrée [1864c], p. 1071).

La durée de sa chute a été évaluée à cinq ou six secondes.[10] (M. Hende, in Daubrée [1864c], p. 1071).

Je ne crois pas me tromper en évaluant à trois secondes la durée de son apparition.[11] (Contre-amiral

[5]The time during which the fireball moved between the two observed points has been evaluated to be 3 seconds.

[6]The duration of the fireball apparition has been a few seconds at most.

[7]Its velocity was less than a shooting star: the duration of its apparition was no more than 5 to 6 seconds.

[8] The duration of the phenomenon has been of a few seconds.

[9]Duration of the phenomenon was a few seconds.

[10]Duration of its fall was evaluated to be 5 to 6 seconds.

[11]I believe not to be wrong when estimating to three seconds the duration of its apparition.

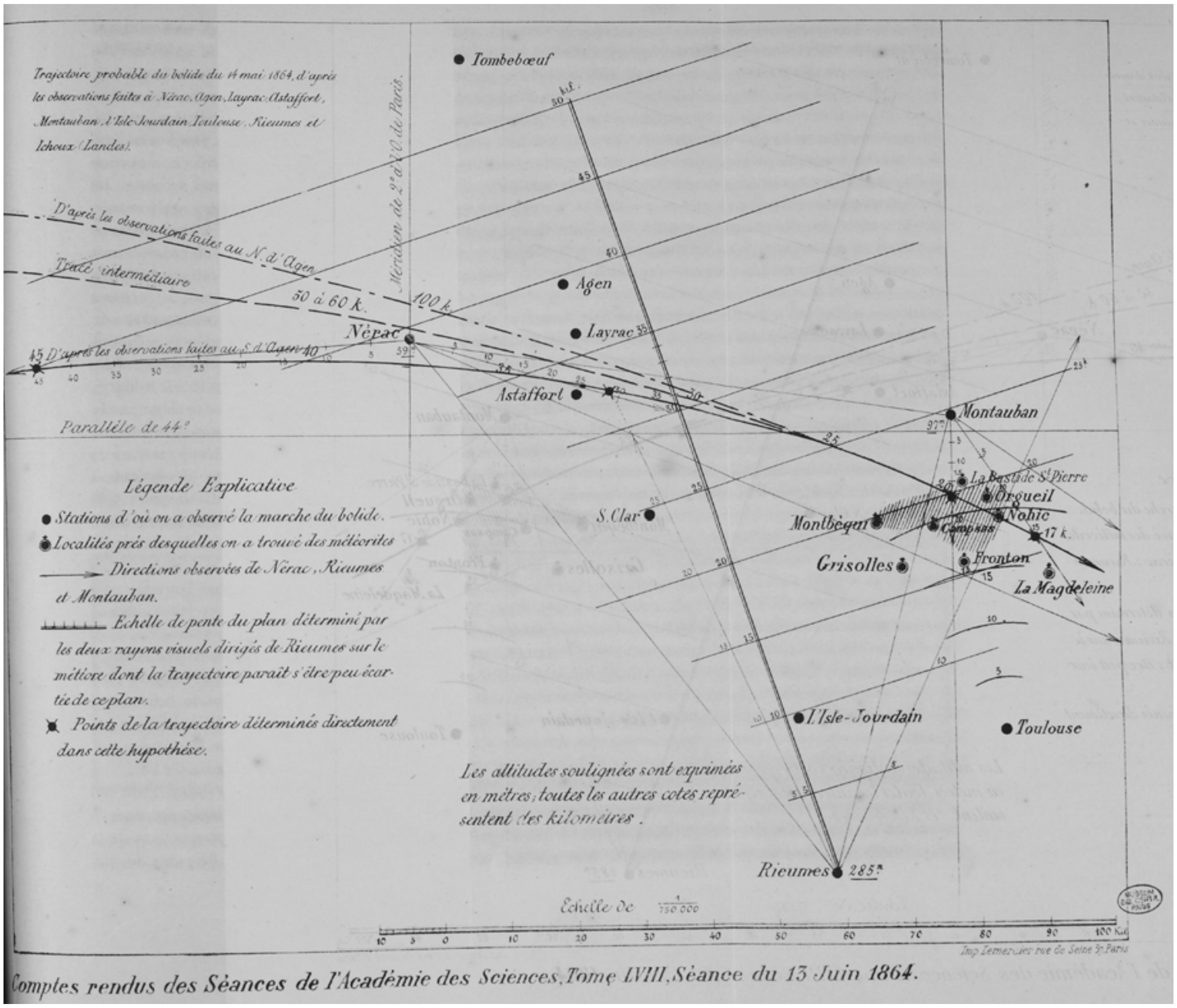

Fig. 5. The trajectory of the Orgueil meteor as calculated by Laussedat in 1864. An intermediary trajectory is plotted between the trajectory deduced from observations performed north and south of Agen. Scale is 1 cm for 8.6 km.

vicomte Fleuriot de Langle, major général du port de Lorient, in Daubrée [1867], p. 18).

From these observations, the most frequent reported number is three seconds (M. Lajous and the viscount Fleuriot). Only one observer (M. Hende) out of four who reported a precise duration refer to a duration as long as five to six seconds (M. Laurentie provides only an upper limit). Although it can be difficult to determine what “a few” (quelques) means precisely, we contend that in French, “quelques” is comparable with “trois” (three), possibly “quatre” (four), but rarely “cinq” (five). For the observers who estimate the duration to be 3 seconds, they would have needed to see only less than one-third of the fireball path (44.4 km) for the atmospheric velocity to be lower than 14.8 km/sec, or for the pre-atmospheric velocity to be lower than 17.8 km/sec. This seems highly unlikely.

In one important case (M. Lajous at Rieumes), the same observer provided both the atmospheric path (~63 km) and the fireball duration (3 sec), leading to an average atmospheric velocity for the Orgueil fireball of 21 km/sec. If one takes into account a possible error of 1 sec on M. Lajous’ estimate of the duration (25% relative), this would yield an atmospheric velocity range between 15.7 and 31.5 km/sec, whose lower limit is still larger than the boundary atmospheric velocity of 14.8 km/sec. We note that M. Lajous saw the fireball at the very end of the trajectory (between 40 and 20 km) when deceleration is at its maximum, and therefore the difference between the pre-atmospheric velocity and the average velocity might be higher than the average adopted value of 20%. We also note that Laussedat (1864) calculated an average atmospheric velocity of 20 km/sec. Unfortunately, he did not go into detail on the method he used to calculate the fireball velocity. Although he undoubtedly had fresher information on the event than we do and was an expert in geodesy, in the absence of an explicit calculation we cannot take his estimate into account, despite the trust he rightly deserves.

When using historical eyewitness data, psychological and sociological factors arise that need to be tackled. The first problem is that of time perception. Are casual observers reliable and able to distinguish between a duration of a few seconds (as they reported here) and a duration larger than 10 seconds? There are four arguments supporting the validity of the reported fireball durations. First, the good agreement between seven different independent observers strengthens the validity of observations (coherent observers). Second, the observers are casual, but concerned enough in the development of science to report their observations to the Academy (trustworthy observers). Third, the language they used is very assertive ("No more than 5 to 6 seconds," "I believe not to be wrong when estimating to three seconds the duration of its apparition": reflexive observers). Finally, confronted by intense luminous signals, observers generally overestimate its duration rather than underestimate it (Fraisse 1984). This means that the estimation of duration by the seven casual observers corresponds to a maximum value, and that the velocity estimates we calculated above are minimal values.

The second issue concerns the accuracy of time-keeping in the mid-eighteenth century in France. This is an interesting problem in its own right. We found clues in the French language edition of the master work of David S. Landes, *Revolution in time, clocks and the making of the modern world*, as well as from literary sources. Clocks having the ability to mark seconds were developed as early as the late seventeenth century (Landes 1987). During the eighteenth century, it became possible to stop the second hand to count time. In the late eighteenth century, clocks marking a fifth of a second were popular among English gentlemen to satisfy their passion for horse racing (Landes 1987). Because continental people were less interested in horses than the English gentry, it took a few generations for clocks with sub-second precision to become widespread in Europe. Among professionals, astronomers and sailors were keen on working with precise clocks. The precision of time-keeping among educated laymen was also directly linked to the development of train travel (Landes 1987). The first commercial train journey in France took place on August 26, 1837. In 1829, a silver watch was precious enough for a young Corsican boy to betray a fugitive[12], but common enough for a warrant officer to own one (Mérimée 1829). The witnesses who wrote letters to Daubrée, among them a sailor, were interested enough in science to take pains to describe the meteor in detail, and communicate their observations to the *Académie des Sciences*. It is likely that they belonged to that group in French society that owned a watch and were well-acquainted with train travel. It is reasonable to assume they had a clear idea of the concept of a second.

To summarize, although the very nature of visual observations prevents a definitive determination of the fireball pre-atmospheric velocity, all the available information points towards a pre-atmospheric velocity larger than 17.8 km/sec. How much larger is difficult to assess. One observation (M. Lajous at Rieumes) yields a pre-atmospheric velocity number ($\nu \sim 25.2$ km/sec), while Laussedat (1864) published the number $\nu \sim 24$ km/sec. In the late 1960s, it has been observed that most meteorites' orbits based on visual observations were flawed, mainly because of poor estimates of the fireball velocity, which frequently led to calculations of hyperbolic orbits (Millman 1969). We note, however, that many of the flawed orbits discussed by Millman (1969) had totally unrealistic beginning heights to start with. The beginning height of the Orgueil orbit is within the range of other observed meteorites falls (Table 2). Moreover, without giving any emphasis to a specific estimate of the velocity that might be flawed, the collective set of all observations point towards a pre-atmospheric velocity larger than 17.8 km/sec. On these grounds, it seems robust enough to conclude that the pre-atmospheric velocity of the Orgueil meteoroid was probably greater than 17.8 km/sec, and therefore that its aphelion distance was greater than 5.2 AU.

As for the trajectory, most of the orbital parameters of Orgueil are unremarkable, and are within the range of previously observed fireballs (Table 5). A pre-atmospheric velocity larger than 17.8 km/sec is not unusual for fireball-producing meteorites (Table 5). Perihelion distance (q) is below 1 AU, as is required for a meteorite whose orbit intersects that of the Earth. The argument of perihelion (ω) and the longitude of the ascending node (Ω) are within the range observed for other meteorite orbits. The inclination (i) is remarkably low. The only other known meteorite fall with such a low inclination is Tagish Lake, which shows other strong similarities with the Orgueil meteorite (Brown et al. 2000; Gounelle et al. 2001; Zolensky et al. 2002). It is also worth mentioning that Murchison, a CM2 chondrite that is, like Orgueil, carbon- and volatile-rich, also has a low inclination ($i = 2.5°$, (Halliday and McIntosh 1990): the Orgueil orbit has an aphelion distance (Q > 5.2 AU) larger than those of the most eccentric orbits hitherto recorded, the Park Forest meteorite pair for which Q = 4.3 AU (Brown et al. 2004). Our analysis indicates that the Orgueil parent body may lie outside the main asteroid belt, contrary to all other meteorites with known orbits.

ORGUEIL: A COMETARY METEORITE?

The Orgueil Tisserand Parameter

Comets are objects dynamically defined by a Tisserand parameter relative to Jupiter:

$$T = \frac{a_J}{a} + 2\cos(i)\sqrt{(1-e^2)\frac{a}{a_J}} \qquad (1)$$

[12]This action cost him life. After his father found out about the betrayal, he executed his own son with a bullet in the head.

Table 4. Properties of the European Network fireballs with significant (>1 kg) terminal mass. ν is the pre-atmospheric velocity and v is the average atmospheric velocity.

EN fireball no.	Name	ν (km/sec)	Length (km)	Duration (sec)	v (km/sec)	ν/v
EN091083	Zdar	15.040	74.07	6.12	12.10	1.243
EN030884	Valec	12.481	94.06	9.16	10.27	1.215
EN041087	Janov	16.064	123.79	9.00	13.75	1.168
EN070591	Benesov	21.181	75.00	4.50	16.67	1.271
EN220495	Kouřim	27.531	109.10	4.78	22.82	1.206
EN231195	Jindrichuv Hradec	22.197	96.40	5.80	16.62	1.336
EN300800	Vimperk	14.915	89.47	6.68	13.39	1.114
EN171101	Turji-Remety	18.483	106.43	6.87	15.49	1.193
EN060402	Neuschwanstein	20.950	90.60	5.30	17.09	1.226
Average value						1.219

Table 5. Comparison of the Orgueil orbit (assuming ν = 20 km/sec for orbital elements other than the aphelion distance) with other known meteorite orbits. Type refers to the petrographic type (Van Schmus and Wood 1967). a is the semimajor axis, e the eccentricity, q the perihelion distance, Q the aphelion distance, ω the argument of perihelion, Ω the longitude of the ascending node, and t_p the date of the perihelion passage. Pr, LC, In, Pe, TL, Mo, Ne, and PF stand for Příbram, Lost City, Innisfree, Peekskill, Tagish Lake, Morávka, Park Forest, and Neuschwanstein, respectively.

	Pr	LC	In	Pe	TL	Mo	Ne	PF	Orgueil
Date of fall	07/04/1959	04/01/1970	06/02/1977	09/10/1992	18/01/2000	06/05/2000	06/04/2000	27/04/2003	14/05/1864
Type	H5	H5	LL5-6	H6	C2-un	H5-6	EL6	L5	CI1
q (AU)	0.79	0.967	0.986	0.886	0.89	0.98	0.79	0.81	0.86
Q (AU)	4.012	2.35	2.758	2.1	3.3	2.71	4.01	4.3	>5.2
ω (°)	241.75	161	177.97	308	222	203.5	241.2	237.5	133
Ω (°)	17.1	283	316.8	17.03	297.9	46.25	16.82	6.12	55
i (°)	10.48	12	12.27	4.9	1.4	32.2	11.31	3.2	0.1
References	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	This work

(1) Ceplecha 1961; (2) McCrosky et al. 1971; (3) Halliday et al. 1978; (4) Brown et al. 1994; (5) Brown et al. 2000; (6) Borovička et al. 2003; (7) Spurný et al. 2003; (8) Brown et al. 2004.

(where a_J is Jupiter's semi-major axis, and a, e, and i the semi-major axis, eccentricity and inclination of the considered orbit), smaller than 3 (Carusi et al. 1987; Levison and Duncan 1997). Short-period ($T < 20$ yr), Jupiter-family comets (JFCs) have a Tisserand parameter between 2 and 3, while long-period ($T > 20$ yr), Halley-type, comets have a Tisserand parameter smaller than 2 (Weissman 1999). Asteroids have a Tisserand parameter larger than 3. If rewritten in terms of perihelion distance (q) and aphelion distance (Q), the equation becomes:

$$T = \frac{2a_J}{q+Q} + 2\cos(i)\sqrt{\frac{2qQ}{(q+Q)a_J}} \quad (2)$$

Calculating the Tisserand parameter for $q = 0.87$ AU, $i = 0.1°$, and $Q > 5.2$ AU (these parameters are well-defined; see discussion above) leads to $T < 2.8$. The orbit of the Orgueil meteorite corresponds to a cometary orbit rather than to an asteroidal orbit. The low inclination of Orgueil orbit is more compatible with Jupiter family comets than with Halley type comets (Weissman 1999).

The question of whether the possible cometary origin of Orgueil (and other CI1 chondrites) is compatible with both cosmochemistry and astronomical data will be addressed in detail in a forthcoming paper. Here, we will content ourselves with discussing the most relevant issues raised by a possible cometary origin for CI1 chondrites. We refer the reader to the review by Campins and Swindle (1998) for a more general discussion on the characteristics of expected cometary meteorites.

Cosmochemistry of CI1 Chondrites

It is important to remember that CI1 chondrites are different from any chondrite group in that they have a chemical composition that is identical (within error) to that of the Sun's photosphere (excepting the lightest elements [Anders and Grevesse 1989]). The bulk chemical composition of comets, which is currently unknown, is also expected to be unfractionated relative to the Sun (Campins and Swindle 1998). When directly compared, the dust fraction of comet Halley is very similar to that of CI1 chondrites (Table 1 of Campins and Swindle 1998).

Ehrenfreund et al. (2001) have measured the relative abundance of amino acids in CI1 chondrites and in other meteorites. Compared to CM2 chondrites, CI1 chondrites have high abundances of β-alanine and glycine that can be made by HCN-polymerization (Ehrenfreund et al. 2001). Because comets are notoriously HCN-rich (e.g., Meier et al. 1998b), this lead Ehrenfreund and collaborators to speculate that CI1 chondrites sample an (extinct) cometary nucleus.

CI1 chondrites are extremely puzzling rocks, since they are the most chemically primitive meteorites and, at the same time, they are petrographically very altered. The mineralogy and texture of CI1 chondrites indicate that these stones have experienced extensive aqueous alteration, most probably within their parent body (Bullock et al. 2005; Zolensky and McSween 1988), although nebular alteration cannot be ruled out. Whether the altering fluid (water) was in the vapor or liquid phase is unknown. The presence of sulfate veins in the CI1 chondrites has long been considered as strong evidence for water circulation on the CI1 parent body (Richardson 1978). Because sulfate veins have most likely formed on Earth as a result of the meteorites' interaction with the atmosphere, there is no longer firm evidence for water circulation (Gounelle and Zolensky 2001). A cryogenic alteration promoted by thin fluid films on the surface of submicrometer grains is also a possibility (Rietmeijer 1985). Aqueous alteration on the CI1 parent body took place early in the history of the solar system, at most ~20 Ma after the formation of the first solids (Endress et al. 1996). It is not yet clear whether it is possible to generate liquid or water vapor in icy bodies that allegedly formed beyond the orbit of Jupiter (Weissman 1999). Possible heat sources are impacts (during or post accretion) or gamma ray–emitting short-lived radionuclides (^{26}Al and ^{60}Fe) (McSween and Weissman 1989). Solar heating, possibly enhanced during a T Tauri phase, is an additional possible heat source. Wallis (1980) calculated that the interior of comets could melt due to the decay of ^{26}Al.

Water in CI1 chondrites has an average D/H ratio of $(172 \pm 3) \times 10^{-6}$ (Eiler and Kitchen 2004). The D/H ratio of the water present in three comets' comae (Halley, Hyakutake, and Hale-Bopp) has been determined by spacecraft observations (Bockelée-Morvan et al. 1998; Eberhardt et al. 1995; Meier et al. 1998a) yielding an average D/H ratio of $(320 \pm 40) \times 10^{-6}$ (Robert 2002). The D/H ratio of comets is roughly twice that of the CI1 chondrites. It should be noted, however, that the D/H ratio of the water present in the coma might be enriched in D relative to the water present in the nucleus because H_2O and D_2O have separate sublimation fronts (Podolak et al. 2002). The three comets that have known D/H ratios are Halley-type comets; the hydrogen isotopic composition of Jupiter-family comets is unknown.

Astronomical and in situ Observations of Comets

The mineralogy of comets, and especially their silicate component, is increasingly well-constrained via the analysis of the 10 μm emission feature of cometary comae (Hanner et al. 1994; Wooden et al. 1999; Wooden et al. 2004). Crystalline pyroxene and olivine grains appear to be abundant in cometary dust, while phyllosilicates have not yet been detected. An upper limit of 1% has been proposed for the abundance of layer-lattice silicates for the Hale-Bopp dust, based on the montmorillonite 9.3 μm spectral feature (Wooden et al. 1999). As far as we know, a similar analysis has not been performed for serpentine. CI1 chondrites are made mainly of an intergrowth of saponite and serpentine (Bass 1971; Tomeoka and Buseck 1988). The total modal abundance of phyllosilicates (serpentine and saponite) is ~70 wt%, while olivine and pyroxene represent less than 10 wt% of the rock (Bland et al. 2004). The absence of astronomical phyllosilicates in cometary dust cannot however be confronted with the abundance of phyllosilicates in CI1 chondrites for two reasons. First, the phyllosilicates in CI1 chondrites are significantly different than terrestrial phyllosilicates, both in their chemical composition, and in their structure (Bass 1971; Tomeoka and Buseck 1988). It is therefore possible that the optical properties of a specific montmorillonite clay (Koike and Shibai 1990), used for modelling the Hale-Bopp spectrum, are quite different from that of the complex mixture of the Orgueil phyllosilicates. Second, the fine-grained and poorly crystalline nature of Orgueil phyllosilicates (Tomeoka and Buseck 1988; Zolensky et al. 1993) might severely limit their infrared emission.

Laboratory infrared reflection spectroscopy of Orgueil (Calvin and King 1997) could potentially be compared to that recorded from the surface of cometary nuclei. Earth-based IR spectra of cometary nuclei are quite rare because of the obscuring effect of the coma. Some data in the 1.3–2.6 μm region have been obtained by the spacecraft Deep Space 1 on the comet Borrelly (Soderblom et al. 2004). The IR absorption peak at 2.7 μm seen in the Orgueil meteorite was absent from the Borrelly data. The reason for this discrepancy might be due to the fact that the IR spectrum of Borrelly records only the very surface of the object, which is known to be highly processed (Soderblom et al. 2004). Alternatively, the Orgueil meteorite could come from slightly below the surface of its cometary parent body, or from a comet that has experienced a different history than Borrelly.

In recent years, comets have transformed from relatively homogeneous astronomical objects into diverse geological bodies (Britt et al. 2004). After the pioneering visit of the Soviet Vesta and the European Giotto spacecrafts to comet Halley in 1986, the USA spacecrafts Deep Space 1 and Stardust have provided imaging of unprecedented precision on the nuclei of comets 19P/Borelly and 81P/Wild 2. Among the wealth of observations and speculations brought by these rendezvous missions, we will discuss the most relevant to our problem.

Cometary surfaces have an abundant non-volatile crust, where volatile refers here to H, C, N, and O ices. In comet Halley, the non-volatile crust covers up to 80% of the nucleus (Sagdeev et al. 1986). The jets originating from the surface are discrete and highly collimated both for Borrelly (Yelle et al. 2004) and Wild 2 (Brownlee et al. 2004), suggesting that most of the surface is covered with non-volatile crust. Perhaps one of the most surprising results of the Stardust fly-by was that Wild 2 was not a rubble pile (Weaver 2004), as is Borelly, and as was thought of most comets (Weissman et al. 2004). Instead it has a cohesive and self-supporting surface (Brownlee et al. 2004). This demonstrates that (1) cometary surfaces possess what would be called in terrestrial geology a "bedrock" (Brownlee et al. 2004); and that (2) comets, though similar when seen from the distance of Earth-based observations, are diverse when studied in a close approach. In terms of a possible cometary origin of CI1 chondrites, these results indicate that rocks such as CI1 chondrites can be a component of a cometary nucleus, and that samples coming from a cometary parent body might show a range of properties. It is worth noting, however, that comet Borrelly's surface cannot be similar to the Orgueil meteorite, since both objects have quite different near-infrared spectra (Calvin and King 1997; Soderblom et al. 2004).

In January 2006, the Stardust capsule, loaded with perhaps as much as 3000 cometary particles larger than 15 μm trapped within aerogel exposed to the coma of Wild 2, will land in the Utah desert. These particles will be available for precise laboratory analysis, providing knowledge of cometary dust comparable only to our knowledge of terrestrial or lunar samples. Were these particles demonstrably similar to CI1 chondrites in term of chemistry and mineralogy, it would give some credit to our hypothesis of a cometary origin of CI1 chondrites.

Although asteroids and comets are at first order radically different objects, both in their dynamic and physical properties, there is certainly some blurring between the two, as demonstrated by the existence of ambiguous objects such as 3200 Phaeton or 4015 Wilson-Harrington (e.g., Campins and Swindle 1998). In other words, there is no reason for the location of the snow line, which defines the limit of water ice condensation (and therefore the physical region of comet formation), and the Jupiter orbit, that defines the dynamic limit of comet formation, to have always strictly coincided over solar system history. A continuum is to be expected from asteroids to comets.

CONCLUSIONS

From the critical examination of visual observations performed 140 years ago by numerous casual witnesses, and reported in several issues of the *Comptes Rendus de l'Académie des Sciences de Paris*, we have calculated the atmospheric trajectory and the orbit of the Orgueil meteorite, which fell on May 14, 1864, at 8 p.m., near Montauban, France. Despite the intrinsic uncertainty of visual observations, we can calculate a reasonably precise atmospheric trajectory, and a moderately precise orbit for the Orgueil meteoroid. Observations from both southern and northern parts of the trajectory, good knowledge of the constellations by nineteenth century educated observers, and accurate and thoughtful reports of the fall by Auguste Daubrée helped considerably in performing good triangulation calculations.

The atmospheric trajectory of the Orgueil meteorite is very similar to that of other meteorites. The atmosphere entry point is estimated to have been ~70 km high and the meteoroid terminal point is estimated to have been ~20 km high. The calculated luminous path is ~150 km with an entry angle of 20°. Five out of six orbital parameters for the Orgueil orbit are well-constrained. The perihelion lies inside the Earth's orbit (q ~ 0.87 AU) and the orbit plane is close to the ecliptic (i ~ 0°). The aphelion distance (Q) depends critically on the pre-atmospheric velocity.

The pre-atmospheric velocity could be estimated from the visual observations to be significantly larger than 17.8 km/sec. This corresponds to an aphelion distance Q larger than the semimajor axis of Jupiter, a_J = 5.2 AU. We therefore suggest that the orbit of the Orgueil meteorite is compatible with that of a comet rather than that of an asteroid. On the basis of its low inclination, a Jupiter-family comet is the most probable parent body for the Orgueil meteorite, although an Halley-type comet cannot be excluded. This is in marked contrast with other meteorites that have an asteroidal orbit (e.g., Spurný et al. 2003).

A cometary origin for the Orgueil meteorite is not unlikely in the light of cosmochemistry and astronomical data. CI1 chondrites are chemically unfractionated relative to the Sun, as comets are expected to be. When directly compared, comet Halley dust and CI1 chondrites have similar chemical compositions (Campins and Swindle 1998). Recent spacecraft observations have shown that cometary nuclei are more geologically complex objects than previously thought (Britt et al. 2004; Brownlee et al. 2004), and might have an abundant non-volatile crust, possibly a source of large boulders that could become CI1 chondrites after their encounter with the Earth, and their classification by meteoriticists.

More generally, if Orgueil (and CI1 chondrites) do indeed have a cometary origin, this has profound implications for our understanding of comets. Contrary to the long-held view that envisions comets as unaltered pristine samples, their rocky component might have endured severe hydrothermal alteration, as recorded in CI1 chondrites. Secondary minerals, such as phyllosilicates and carbonates, should be an important component of cometary solids. Though completed 140 years after the fall, the determination of the Orgueil meteorite orbit is timely, since the Stardust spacecraft collected solid samples of comet Wild 2 on January 2, 2004. We look forward to laboratory analyses of these samples (due on Earth January 15, 2006) and their comparison to CI1 chondrites. In any case, independent of the possible cometary origin of Orgueil and the results yielded by the Stardust mission, a continuum between asteroids and comets is expected in our solar system, smoothing the possibly provocative proposition that five cometary meteorites are already present within terrestrial museums.

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