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The Ardón L6 ordinary chondrite: A long-hidden Spanish meteorite fall

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Abstract–We report and describe an L6 ordinary chondrite fall that occurred in Ardón, León province, Spain (longitude 5.5605°W, latitude 42.4364°N) on July 9th, 1931. The 5.5 g single stone was kept hidden for 83 yr by Rosa González Pérez, at the time an 11 yr old who had observed the fall and had recovered the meteorite. According to various newspaper reports, the event was widely observed in Northern Spain. Ardón is a very well-preserved, fresh, strongly metamorphosed (petrologic type 6), and weakly shocked (S3) ordinary chondrite with well-equilibrated and recrystallized minerals. The mineral compositions (olivine $Fa_{23.7\pm0.3}$, low-Ca pyroxene $Fs_{20.4\pm0.2}Wo_{1.5\pm0.2}$, plagioclase $An_{10.3\pm0.5}Ab_{84.3\pm1.2}$), magnetic susceptibility (log $\chi = 4.95 \pm 0.05 \times 10^{-9}$ m^3 kg^{-1}), bulk density (3.49 $\pm$ 0.05 g cm^{-3}), grain density (3.58 $\pm$ 0.05 g cm^{-3}), and porosity (2.5 vol%) are typical for L6 chondrites. Short-lived radionuclides confirm that the meteorite constitutes a recent fall. The ^{21}Ne and ^{38}Ar cosmic ray exposure ages are both about 20–30 Ma, similar to values for many other L chondrites. The cosmogenic ^{22}Ne/^{21}Ne ratio indicates that preatmospheric Ardón was a relatively large body. The fact that the meteorite was hidden in private hands for 83 yr makes one wonder if other meteorite falls may have experienced the same fate, thus possibly explaining the anomalously low number of falls reported in continental Spain in the 20th century.

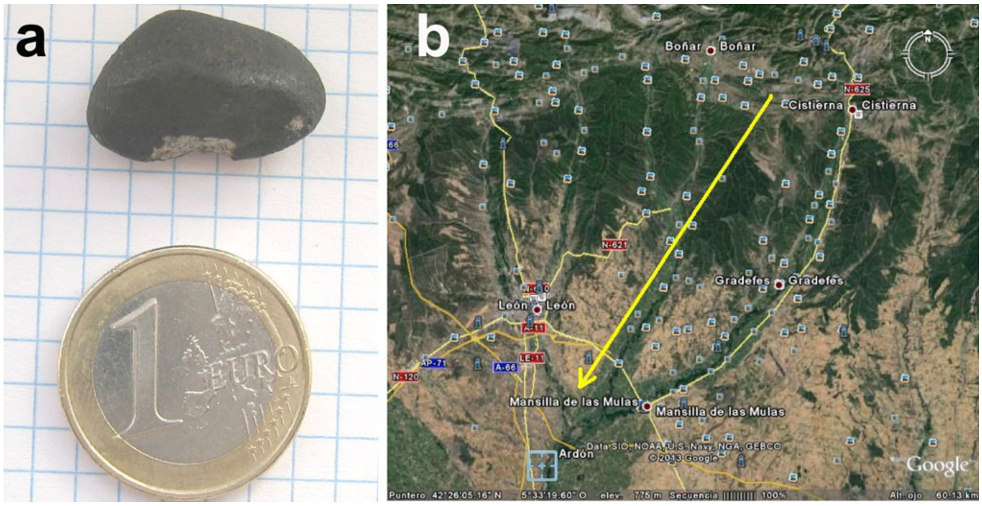

Fig. 1. a) The 5.48 g Ardón meteorite as it arrived at the Institute of Space Sciences (CSIC-IEEC); the 1 Euro is approximately 21 mm in diameter. b) The estimated trajectory of the Ardón bolide projected onto the ground based on the available press reports, and fitting the meteorite fall in Ardón.

INTRODUCTION

We report, describe, and classify a meteorite that fell on July 9th, 1931. The fall was witnessed by Rosa González Pérez, an 11 yr old girl at the time, who saw the 5.48 g stone (Fig. 1) falling right next to her in a known Ardón street with the exact coordinates, longitude 5.5605°W and latitude 42.4364°N (altitude 785 m). To our knowledge, no additional specimens were recovered. Rosa heard a loud explosion, followed by thunder that was associated with a bright meteorite-dropping bolide flying over León province at approximately 9 h 20 m UTC (same local time). This event was also documented and reported in local newspapers and widely observed in León province and could also be heard in the province capital (León) and other towns like Boñar and Cistierna. It is fascinating to note that Rosa González Pérez kept the meteorite hidden in her home for 83 yr, until the now 94 yr old explained the event to her nephew, José Antonio González. He wondered about the importance of this meteorite recovery: perhaps his aunt's recovery a long time ago might be relevant to science, and even to his town and country. The increasing public interest in meteorites was the reason why the owners recently informed us of the meteorite's existence and most generously provided samples for our studies (Fig. 1). Rosa González Pérez reported that she collected the specimen from the ground immediately after the fall "having the feeling that the meteorite was still hot." She decided to keep the specimen in a box as a memory of this event, where it has been extraordinarily well preserved.

TRAJECTORY OF THE ARDÓN FALL

The likely trajectory of the Ardón meteorite fall projected on the ground is shown in Fig. 1b, reconstructed to be compatible with the press reports published at the time. Thus, the projection on the ground of the terminal point of the luminous trajectory of the bolide seems to be located in the surroundings of Ardón, although the exact position cannot be established because the available reports are too vague. According to the newspaper "Diario de León" from the town of Las Salas, the fireball was witnessed over Valdelinares and a continuous vibration (a shock-induced earthquake ground vibration) was felt. This information helped to establish the likely flight direction. Another press report published by "Diario Gaditano" describes the vibration felt by the inhabitants of Cistierna and Boñar, which would imply that the initial point of the luminous trajectory was located at a higher latitude than that of these towns. But, again, the exact position cannot be specified. Another constraint to the likely trajectory appears in the reports in the newspapers "La Independencia" and "Diario de León," which state that witnesses from Cistierna and Boñar were located on both sides of the atmospheric path of the event. This would imply that the fireball flew toward Ardón with a trajectory located between these two towns.

ANALYTICAL PROCEDURES AND DATA REDUCTION

Three polished thin sections were prepared, and high-resolution mosaics were made of the sections using

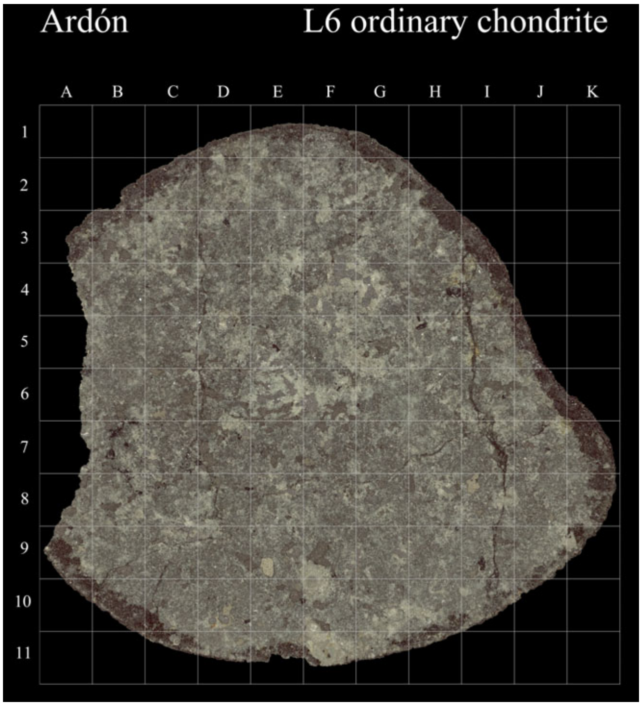

Fig. 2. Mosaic of a polished section of the Ardón L6 chondrite archived at the Institute of Space Sciences (CSIC). Squares are 1 mm.

a Zeiss Scope petrographic microscope at 50× magnification. About 100 pictures of each section were merged to create the mosaics (Fig. 2). A grid of the images of the sections allowed identifying the main features by micro-Raman spectroscopy, SEM, and microprobe analysis. A petrographic microscope was also used to characterize the main minerals. Two of the sections are preserved at the Institute of Space Sciences (CSIC-IEEC), Barcelona, and the third in the Institut für Planetologie, Münster.

A JEOL 6610-LV electron microscope at the Interdisciplinary Center for Electron Microscopy and Microanalysis (ICEM) was employed to resolve the fine-grained recrystallized textures of the rock and those in the shock veins. An attached energy-dispersive X-ray spectrometer (EDS) system (INCA; Oxford Instruments) helped in the chemical characterization of the main mineral constituents.

Quantitative mineral analyses were obtained with a JEOL JXA 8900 Superprobe electron microprobe (EPMA) at Münster operated at 15 keV and with a probe current of 15 nA. Natural and synthetic standards were used for wavelength-dispersive spectrometry. Counting times for all elements were 10 s peak and 5 s background, except for Na and K with 5 s peak and 2.5 s background. Matrix corrections were made according to the $\Phi\rho(z)$ procedure (Armstrong 1991). Cobalt concentrations in metal grains obtained by EPMA are systematically higher due to overlap of the Fe K_β with the Co K_α line. These values for kamacite as well as for taenite were corrected by applying a correction factor of 0.65, which was determined from Co EPMA data obtained on kamacite grains from the Almahata Sitta E chondrites MS-13, MS-17, and MS-155 in the same analytical session that were compared with Co data collected from the same grains by LA-ICP-MS (Horstmann et al. 2014), where this overlap is not a concern.

A scanning electron microscope FEI Quanta 650 FEG working in a low-vacuum BSED mode was used in Barcelona for elemental analysis of the samples using an EDX Inca 250 SSD XMax20 detector with an active area of 20 mm^2. Micro-Raman spectra with a spot size of approximately 1 μm and laser power on the sample below 0.6 mW were recorded to provide chemical and structural information of some phases. Measurements were carried out in backscattered geometry at room temperature using the 5145 Å line of an Argon-ion laser with a Jobin-Yvon T-64000 Raman spectrometer attached to an Olympus microscope and equipped with a liquid nitrogen–cooled CCD detector. The Raman spectrometer allowed acquisition of high-resolution spectra in working windows between 100 and 1400 cm^{-1}.

The trace element composition of the meteorite was measured with ICP-MS at UCLM in Toledo, using a thermo electron XSeries II apparatus. To ensure matrix similarity between calibration standards and samples, geological CRMs of the United States Geological Survey (AGV-2, BCR-2, GSP-2, SDC-1, BHVO-2, and BIR-1) were used for external calibration. Rhodium was used as internal standard. The solutions of the sample, Certified Reference Materials, and blanks were obtained by alkaline fusion with $LiBO_2$ in Pt-Au crucibles, followed by acid dissolution of the melt: 0.0377 g of sample and 100 mg of flux were fused and the melted glass was poured into a Teflon beaker containing 100 mL HNO_3 0.3N.

Magnetic susceptibility measurements were performed of the meteorite at 300.00 ± 0.02 K with a Quantum Design MPMS-XL SQUID magnetometer at UPC in Barcelona.

Oxygen isotopes were analyzed at Göttingen by laser fluorination in combination with dual inlet gas source mass spectrometry (Sharp 1990). Samples were heated and melted in a F_2 atmosphere. The oxides react to form fluorides and sample O_2 is released. The O_2 is cleaned from contaminants by cold traps and gas chromatography. The latter ensures complete removal of NF_3 from the sample gas, which would interfere in the analysis of ^{17}O and to much lesser extent of ^{18}O.

The uncertainties in the determination of $\delta^{17}O$ and $\delta^{18}O$ are about ±0.15 and ±0.20 ‰, respectively (note that these uncertainties are correlated), and for $\Delta^{17}O$ about ±0.01 ‰. For details of the technique and definitions, see Pack and Herwartz (2014).

Short-lived cosmogenic radionuclides, long-lived cosmogenic ^{26}Al, and natural radioactivity were measured for 7 days using nondestructive gamma-ray spectroscopy. The remaining 4.4 g fragment of Ardón was measured in the STELLA (SubTErranean Low Level Assay) facility of underground laboratories at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, using a high-purity germanium (HPGe) detector of 460 cm^3 (Arpesella 1996). The counting efficiencies were calculated using a Monte Carlo code. This code was validated through measurements and analyses of samples of well-known radionuclide activities and geometry. The uncertainties in the radionuclide activities are dominated by the uncertainty in the counting efficiency, which is conservatively estimated to be 10%. Average density and composition for L chondrites were assumed for the data reduction and were taken from Britt and Consolmagno (2003), and from Jarosewich (1990), respectively.

Helium, Ne, and Ar concentrations and isotopic compositions were measured at ETH Zürich in a 31 mg single chip. Gases were extracted in one heating step at approximately 1800 °C and analyzed according to procedures described by Wieler et al. (1989).

RESULTS

Mineralogy, Petrology, Shock Metamorphism, and Trace Element Composition

The fusion-crusted meteorite Ardón has a well-recrystallized texture (Figs. 3–5) with only some chondrule relics (Figs. 3b and 5b) of former barred olivine (BO) and/or radial pyroxene (RP) chondrules (Fig. 5). These relic chondrules are of normal apparent size (400–800 μm). No macrochondrules (≥3 mm), often still visible in metamorphosed type 6 ordinary chondrites (Weyrauch and Bischoff 2012), were observed in Ardón. Many ordinary chondrites are breccias (e.g., Bischoff et al. 1993, 2006, 2013). Some of these, e.g., Villalbeto de la Peña (Bischoff et al. 2013), experienced metamorphism and recrystallization after brecciation and lithification. As some fine-grained, fragment-like objects were found in Ardón, it is not absolutely clear if this rock belongs to this type of recrystallized breccia (see below; Fig. 5c).

Olivine is by far the most abundant mineral phase in Ardón. Generally, the grains are variable in size and homogeneous in composition throughout the entire polished thin section. The mean composition of 22 olivine grains is $Fa_{23.7\pm0.3}$ with a compositional range of $Fa_{23.1\text{–}24.4}$ (Table 1). Analyses of 19 low-Ca pyroxene grains give a mean composition of $Fs_{20.4\pm0.2}Wo_{1.5\pm0.2}$ with a total range of $Fs_{20.0\text{–}20.7}Wo_{1.1\text{–}2.0}$. (Table 1). Plagioclase grains of variable sizes are present; large crystals often exceed 100 μm in size. Mean plagioclase (24 analyses) is $An_{10.3\pm0.5}Ab_{84.3\pm1.2}$, with total ranges of $An_{9.2\text{–}11.5}Ab_{81.8\text{–}86.3}$ (Table 1). Metallic Fe,Ni and sulfide typically occur as small grains distributed throughout the entire section. Some grains related to the formation of shock veins are elongated (Fig. 4a). Near the fusion crust metal-sulfide intergrowths with a cellular (checkerboard) texture have been found (Fig. 4b). Kamacite has mean Ni- and Co-concentrations of 5.9 (range: 5.2–6.2) and 0.60 (0.46–0.72) wt%, respectively. Taenite has variable Ni concentrations of 23–33 wt% (mean: 26.6 wt%) and mean Co values of 0.42 wt% (range: 0.20–0.59 wt%). Troilite is an abundant phase, and is homogeneously distributed throughout the entire rock. Chromite occurs as accessory and small grains with MgO-, Al_2O_3-, and TiO_2-concentrations of about 2.6, 5.8, and 2.8 wt%, respectively (Table 1). In addition, some ilmenite and phosphate grains were also identified (Figs. 3c and 4c). One ilmenite grain has 4.2 wt% MgO and 1.8 wt% MnO (Table 1). In general, the rock has many textural and mineralogical similarities to the recent Jesenice (L6) meteorite fall (Bischoff et al. 2011).

Like many other L6 chondrites, Ardón shows distinct shock features such as shock-modified minerals and shock veins (Figs. 4a and 5b). Typically, Ardón olivine is characterized by having strong undulatory extinction and planar fractures (Fig. 5a). Some olivine grains show weak mosaicism, but their abundance is certainly below 25%. Thus, the optical features indicate that the rock is weakly shocked (S3; Stöffler et al. 1991; Bischoff and Stöffler 1992). Some areas were found within Ardón that may be related to former lithic clasts that were recrystallized upon metamorphism. One fine-grained area partly bordered by a shock vein is shown in Fig. 5c.

As the specimen was recovered immediately after the fall, the residence time of 83 yr on Earth in a jewel box in the home of Rosa González Pérez did not affect the rock by terrestrial weathering. Thus, it is very fresh, with weathering grade W0 of Wlotzka (1993). Finally, the trace element composition of Ardón is given in Table 2. An inductively coupled plasma mass spectrometer (ICP-MS) Thermo Electron X Series II was used at UCLM (Toledo) for minor and trace elements. A chip of 38 mg was used, so due to the small sample available for the analyses we cannot discard some element differences compared with other L chondrite falls. The data agree within a factor of two with the literature data for L chondrites listed in Lodders and Fegley (1998).

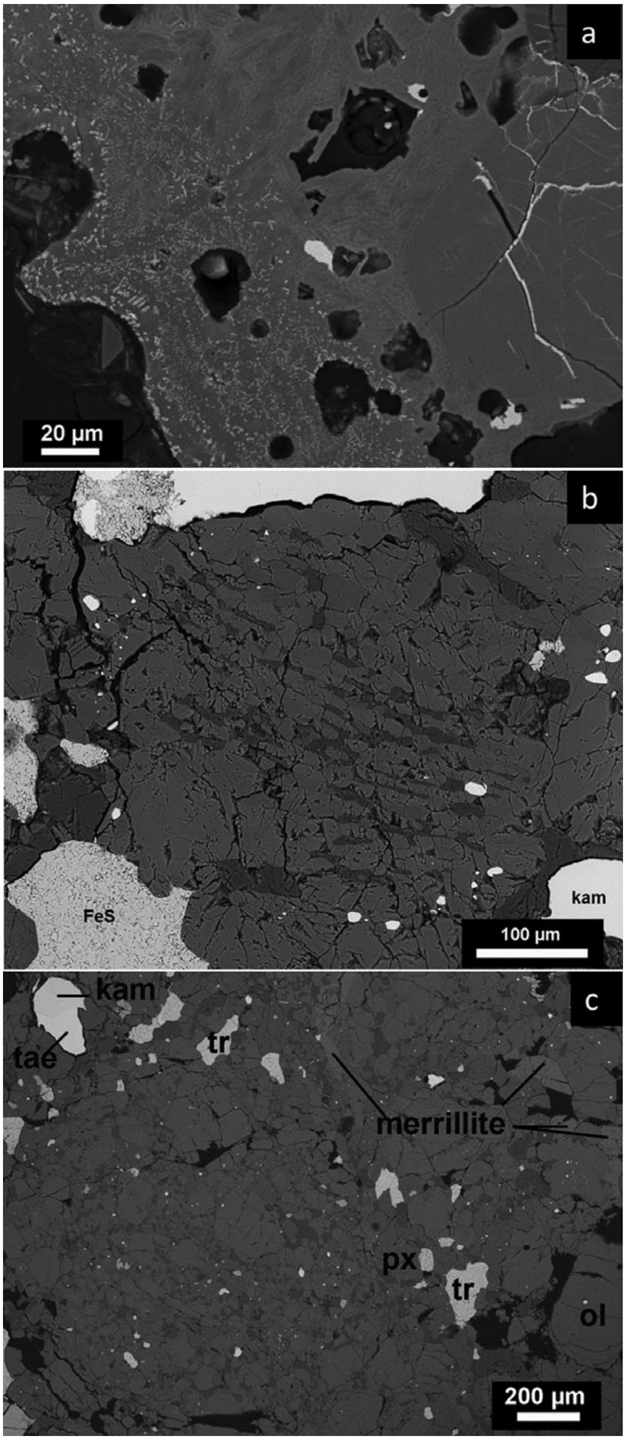

Fig. 3. BSE images of typical textures in Ardón. a) Fusion crust of the meteorite; small magnetite grains are visible (light gray) at the outer border of the rock; b) a relict BO chondrule surrounded by metal and sulfide; c) a recrystallized area consisting of abundant olivine (ol) and pyroxene (px) grains and minor plagioclase (dark gray) associated with metal, sulfide, and merrillite. kam = kamacite, tae = taenite, tr = troilite. The left part of the image shows what may have been a former porphyritic chondrule.

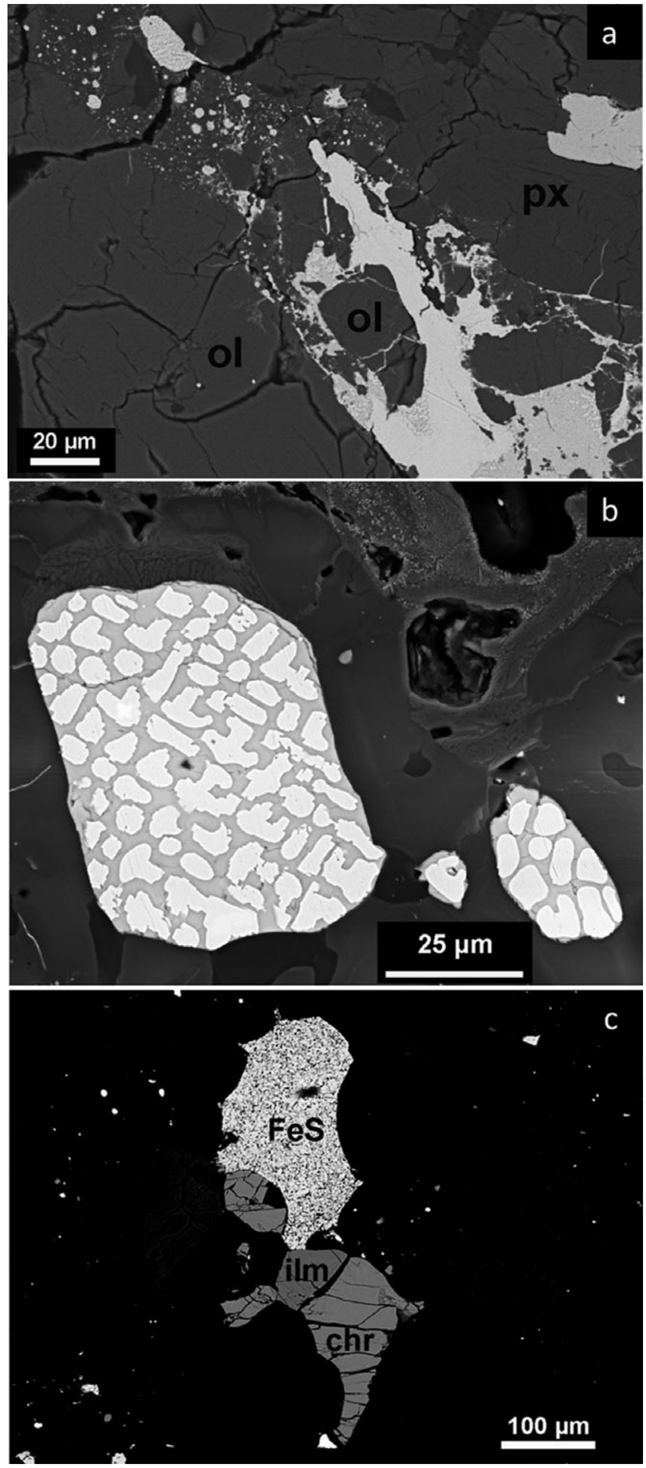

Fig. 4. BSE images of a) a shock vein that mainly consists of metal-sulfide intergrowths embedding silicate fragments. In the upper left part metal-sulfide spherules are enclosed in the silicate-rich melt of the vein; b) metal-sulfide intergrowth with a cellular (checkerboard) texture within the fusion crust of the meteorite (metal: white); c) intergrowth of ilmenite (ilm), chromite (chr), and troilite (FeS) enclosed in silicates (black).

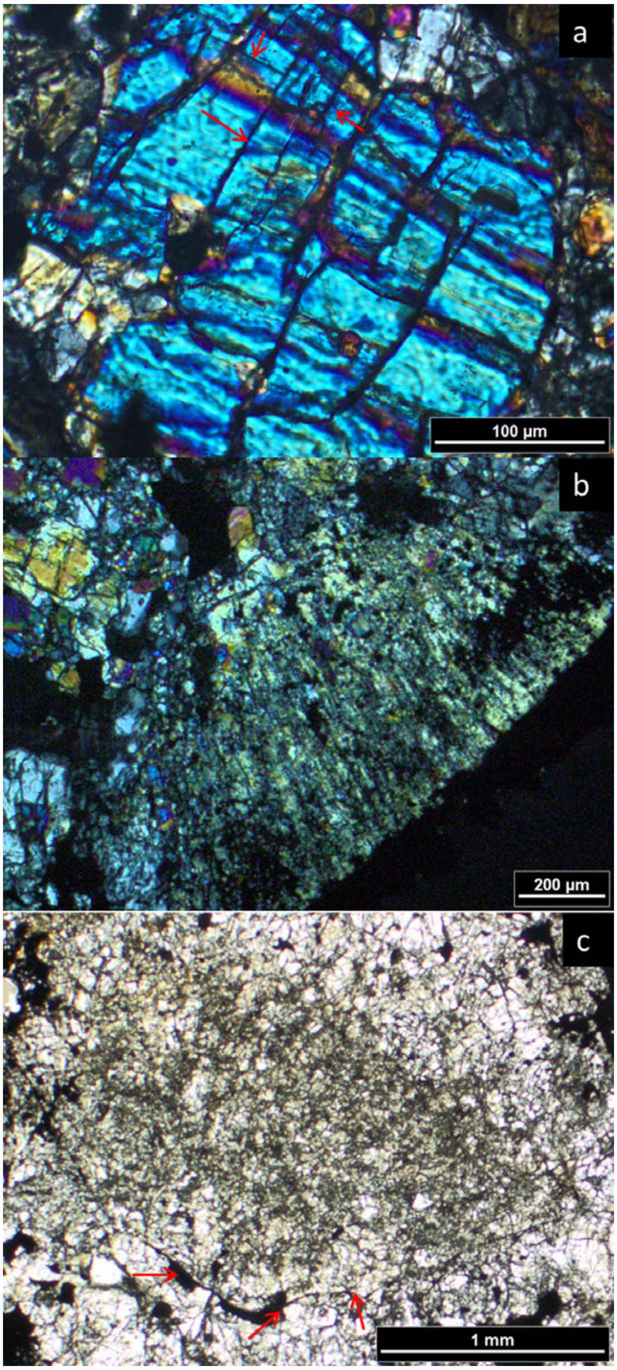

Fig. 5. Photomicrographs of a) an olivine grain showing planar fractures (red arrows), indicating that the meteorite is weakly shocked (S3); b) relict fragment of a radial pyroxene (RP) chondrule. Both images are taken in transmitted light, crossed polarizers; c) image in transmitted light of a possible fine-grained clast surrounded by a shock vein (marked with red arrows).

Magnetic Susceptibility, Density, and Porosity

Specific magnetic susceptibility, χ, gave a log χ of 4.95 ± 0.05 (in 10^{-9} m^3 kg^{-1}). The bulk density of the meteorite, ρ_b, is 3.49 ± 0.05 g cm^{-3}. The grain density (ρ_g, density that excludes pores and voids) was determined with a helium pycnometer and is 3.58 ± 0.05 g cm^{-3}. From the grain and bulk density values, the porosity of the Ardón meteorite was calculated to be 2.5%.

Oxygen Isotopes and Noble Gases

The bulk oxygen isotope composition of Ardón is $\delta^{17}O_{VSMOW} = +3.83‰$ and $\delta^{18}O_{VSMOW} = +5.23‰$. It identifies the specimen as an ordinary chondrite and falls in the overlapping fields of L and LL ordinary chondrites (Clayton et al. 1991; Fig. 6).

The noble gas data (Table 3) indicate that Ne is entirely cosmogenic without any primordial Ne, as expected for an ordinary chondrite of high petrologic type. The sample is obviously also free of solar-wind Ne, i.e., Ardón is not a regolith breccia. The low $^{22}Ne/^{21}Ne$ ratio of 1.06 indicates substantial shielding, which makes the determination of the noble gas exposure age rather uncertain. Following Dalcher et al. (2013) by assuming a preatmospheric size of Ardón of less than 65 cm and an atmospheric ablation loss of at least 85%, at $^{22}Ne/^{21}Ne = 1.06$, we obtain nominal ^{21}Ne and ^{38}Ar production rates (in $10^{-8}cm^3$STP $[g*Ma]^{-1}$) of 0.466 and 0.0550, respectively, and, hence, single-stage ^{21}Ne and ^{38}Ar exposure ages of approximately 20 and 19 Ma, respectively. However, these nominal production rates may well have to be considered as upper limits (Dalcher et al. 2013), and it seems therefore likely that the true (single-stage) exposure age of Ardón is somewhat higher than approximately 20 Ma. This is also suggested by combining the ^{26}Al and the ^{21}Ne data and using the average $^{21}Ne/^{26}Al$ production rate ratio proposed by Dalcher et al. (2013), which results in a ^{21}Ne production rate for Ardón of $(0.30 \pm 0.06) \times 10^{-8}$ cm^3 STP $(g*Ma)^{-1}$, considerably lower than the value deduced from $^{22}Ne/^{21}Ne$ above. The resulting ^{26}Al-^{21}Ne exposure age is approximately 31 ± 6 Ma. Indeed, exposure ages in the range of 20–30 Ma are common for L chondrites (Marti and Graf 1992). In any case, we conclude that preatmospheric Ardón was quite a large body, although this statement cannot easily be quantified.

The concentration of radiogenic ^4He of 391×10^{-8} cm^3 STP g^{-1} (corrected for cosmogenic ^4He with $[^3He/^4He]_{cos} = 0.16$) yields a nominal U-Th-^{4}He age of 1.28 Ga, for typical L-chondritic U-Th concentrations. Similarly, the concentration of ^{40}Ar (assumed to be entirely radiogenic) yields a nominal K-Ar age of 3.95 Ga. Many L chondrites had their U-Th-He and K-Ar clocks partly or completely reset by the collision, which disrupted the L chondrite parent

Table 1. Average compositions of minerals in Ardón, obtained by electron microprobe analyses (in wt%, except for endmember compositions, which are in mol%).

	Olivine	Pyroxene	Plagioclase	Chromite	Ilmenite
n	22	19	24	4	1
Na_2O	b.d	0.02 ± 0.02	9.7 ± 0.3	b.d.	b.d.
Al_2O_3	b.d.	0.15 ± 0.02	20.3 ± 0.2	5.8 ± 0.1	b.d.
K_2O	b.d.	b.d.	0.95 ± 0.17	b.d.	b.d.
Cr_2O_3	b.d.	0.11 ± 0.04	b.d.	55.3 ± 0.3	0.25
MgO	38.9 ± 0.3	28.7 ± 0.2	0.04 ± 0.11	2.65 ± 0.09	4.2
SiO_2	37.8 ± 0.2	54.6 ± 0.3	64.3 ± 0.6	b.d.	b.d.
CaO	b.d.	0.77 ± 0.11	2.14 ± 0.07	0.02 ± 0.02	0.03
MnO	0.46 ± 0.03	0.49 ± 0.03	b.d.	0.77 ± 0.02	1.76
TiO_2	b.d.	0.17 ± 0.03	0.04 ± 0.02	2.84 ± 0.06	53.6
FeO	21.6 ± 0.3	13.3 ± 0.1	0.31 ± 0.10	30.0 ± 0.1	38.9
Fo/En/Ab	76.3 ± 0.3	78.1 ± 0.2	84.3 ± 1.2		
Fa/Fs/An	23.7 ± 0.3	20.4 ± 0.2	10.3 ± 0.5		

n = number of analyzed grains, b.d. = below detection limit.

Table 2. Trace element composition of the Ardón meteorite.

Element	ppm	Element	ppm	Element	ppm
V	57.22	Mo	1.15	Dy	0.28
Cr	2794.59	Cs	0.10	Ho	0.06
Co	427.03	Ba	29.49	Er	0.24
Ni	7883.78	La	0.73	Tm	0.03
Cu	88.95	Ce	2.32	Yb	0.19
Zn	81.78	Pr	0.19	Lu	0.03
Rb	2.44	Nd	0.82	Hf	0.26
Sr	27.35	Sm	0.23	Ta	0.02
Y	1.73	Eu	0.10	Pb	81.86
Zr	10.45	Gd	0.24	Th	0.25
Nb	0.36	Tb	0.04	U	0.05

body approximately 470 Ma ago (Bogard 2011). It is possible, but cannot be proven by the data at hand, that also Ardón partly lost its radiogenic noble gases in this event. The low $^{3}He/^{21}Ne$ ratio of approximately 2.7 also indicates loss of cosmogenic ^{3}He.

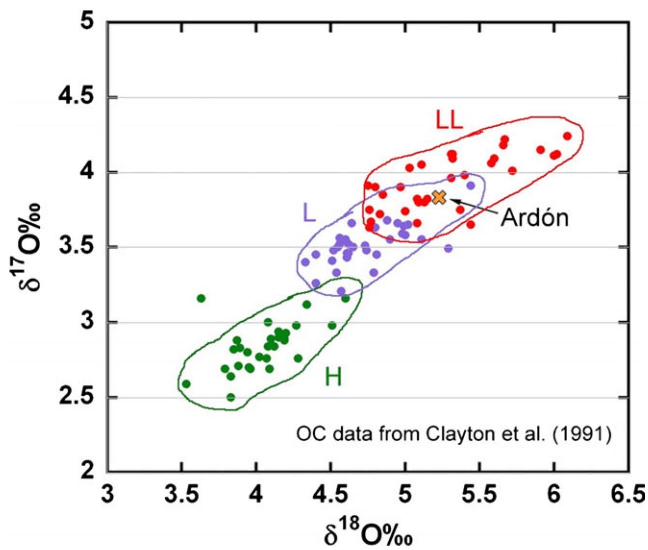

Fig. 6. Plot of the oxygen isotope composition of Ardón in comparison to other ordinary chondrites (data from Clayton et al. 1991). Ardón falls in the overlapping fields of L and LL ordinary chondrites.

Short-Lived and Long-Lived Radionuclides

The measured activity concentrations for the cosmogenic radionuclides ^{22}Na (half-life 2.60 a) of <4.7, ^{26}Al (half-life 7.05×10^5 a) of 52 ± 8, and ^{60}Co (half-life 5.27 a) of <3.1 are for the reference time for the given activities at the start of the measurement (July 16th, 2013). For ^{22}Na and ^{60}Co only upper detection limits can be reported. The elemental concentrations of Th (40 ± 10 ng g^{-1}), U (<13 ng g^{-1}), and K (990 ± 110 µg g^{-1}) are within uncertainties in agreement with the average concentrations given by Wasson and Kallemeyn (1988) for L chondrites. Note that these data include a 1σ uncertainty of approximately 10% in detector efficiency.

DISCUSSION

Classification of Ardón

Many of the data obtained in this study of Ardón, when compared with data published in the literature, clearly indicate that the meteorite is an S3L6 ordinary chondrite. The L group classification of this equilibrated chondrite is evident from the compositions of the meteorite's constituent minerals (Table 1). For example, the mean compositions of olivine ($Fa_{23.7\pm0.3}$) and low-Ca pyroxene ($Fs_{20.4\pm0.2}Wo_{1.5\pm0.2}$) are very close to the ranges in $Fa_{22.7–25.6}$, mean $Fa_{24.6}$, and $Fs_{18.7–22.6}$, mean

Table 3. He, Ne, and Ar in Ardón.

Measured concentrations (10^{-8} cm^3STP g^{-1})									
^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	$^{22}Ne/^{21}Ne$	^{36}Ar	^{38}Ar	$^{38}Ar_c$	^{40}Ar
25.5	549	8.46	9.31	9.87	1.060	1.541	1.186	1.021	4590

Uncertainties of concentration values approximately 4%, uncertainties of Ne isotopic composition and $^{36}Ar/^{38}Ar$ approximately 0.5%. Measured ^{3}He and all Ne isotopes assumed to be entirely cosmogenic, while cosmogenic $^{38}Ar_c$ was calculated by assuming measured ^{36}Ar and ^{38}Ar to be a two-component mixture of trapped Ar ($^{36}Ar/^{38}Ar = 5.32$) and cosmogenic Ar ($^{36}Ar/^{38}Ar = 0.65$), i.e., assuming negligible ^{36}Ar produced by neutron capture on ^{35}Cl.

$Fs_{21.3}$ for L group chondrites given by Keil and Fredriksson (1964), as modified by Fodor et al. (1976). Furthermore, the mean plagioclase composition for Ardón is $An_{10.3\pm0.5}Ab_{84.3\pm1.2}$, with ranges of $An_{9.2–11.5}$ $Ab_{81.8–86.3}$. This is also very close to the mean plagioclase compositions given in the literature for L chondrites of $An_{10.2}Ab_{84.2}$ (Van Schmus and Ribbe 1968). Similarly, chromite in Ardón compositionally resembles L group chromite as given by Bunch et al. (1967) (wt% literature data in brackets: TiO_2 2.84 [2.81]; Cr_2O_3 55.3 [56.1]; FeO 30.0 [33.0]; MnO 0.77 [0.74]; MgO 2.65 [1.99], and so does ilmenite as given by Snetsinger and Keil [1969]: FeO 38.9 [41.9]; MnO 1.76 [1.5]; MgO 4.2 [3.3]). Finally, a number of physical property measurements confirm the classification of the meteorite as an L group chondrite: The bulk density of Ardón, ρ_b, of 3.49 ± 0.05 g cm^{-3} is within the 3.40 ± 0.15 g cm^{-3} range for L6 chondrites (Wilkinson and Robinson 2000), and the grain density, ρ_g, of 3.58 ± 0.05 g cm^{-3} is very close to the average grain density of 3.56 ± 0.1 of L group chondrites given by Consolmagno et al. (2008). Furthermore, the magnetic susceptibility and density are commonly correlated for meteorite falls, as both are intensive variables that vary with iron content (Britt and Consolmagno 2003; Consolmagno et al. 2006). The values of magnetic susceptibility for Ardón gave a log χ of 4.95 ± 0.05 (in 10^{-9} m^3 kg^{-1}), similar to other L chondrite falls, 4.87 ± 0.10 (Rochette et al. 2003; Consolmagno et al. 2006) and 4.87 ± 0.08 (Smith et al. 2006), and the magnetic susceptibility and density of Ardón plot well within the L chondrite group in χ versus ρ_b and χ versus ρ_g graphs for meteorite falls (Consolmagno et al. 2006).

The petrologic type 6 and the S3 shock classification of this meteorite is evident from microscopic studies of polished thin sections, where only a very small number of chondrule relicts are visible and plagioclase grains much larger than 100 µm in apparent size occur. Thus, Ardón is highly recrystallized, and these characteristics clearly indicate that the metamorphosed rock is of petrologic type 6. Typical Ardón olivine shows undulatory extinction and planar fractures. These features indicate that the rock is weakly shocked (S3), using the classification scheme for shock metamorphism of Stöffler et al. (1991).

The “Missing” Spanish Meteorites

Spain is one of the countries where the recoveries of meteorite falls are statistically lower than the expectations made on the basis of fireball networks (Halliday et al. 1996). With a surface area of about half a million km^2, continental Spain should have about 1.5 meteorite falls with a surviving mass larger than 1 kg every year. However, the number of recoveries is far lower, but this situation has changed somewhat since 1999, thanks to the cooperative effort made by scientists integrated in the Spanish Meteor and Fireball Network (www.spmn.uji.es). Within this framework, two meteorite falls, Puerto Lápice and Villalbeto de la Peña, have been recovered and studied in the last decade (e.g., Llorca et al. 2005, 2009; Trigo-Rodríguez et al. 2006, 2009; Dyl et al. 2012; Bischoff et al. 2013). And there is another curious fact about Spanish meteorite falls: There were 1 falls recovered during the 19th century, but only five during the 20th century, and all of them during the first half of the century (Table S1). However, the rarity of recovery of meteorites in general and in Spain specifically might also be because, while most meter-sized meteoroids and small near-Earth objects (NEOs) penetrating the atmosphere produce extremely bright bolides, they may be producing very small terminal masses that might not get recovered. In fact, while studies of the deceleration in the atmosphere of meteoroids with initial masses of few tens of kg usually end up predicting nonzero terminal masses (Trigo-Rodríguez et al. 2007; Madiedo et al. 2013), it might, in practice, be difficult to find and recover meteorites of only a few centimeters in size. Thus, one wonders if some tiny meteorite falls may have shared the fate of Ardón: They may have been recovered, but not reported and may be hidden in some private jewel box, as was Ardón for 83 yr!

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

Table S1: Recognized Spanish meteorite falls listed in chronological order, including the respective community, petrographic classification, and total known weight (TKW) according to the Meteoritical Bulletin Database. Ardón is given in bold, being the fall with the smallest TKW. Five doubtful meteorites are not listed.