(*Quarterly Journal of the Royal Astronomical Society* 27, 1986, pp. 212–236), and can be found in the society's library. The fate that befell Denning's several telescopes is not so clear. It is likely that they may no longer exist as functioning instruments.

[26] M. Beech, "The Stationary Radiant Debate Revisited", *Quarterly Journal of the Royal Astronomical Society* 32, 1991, pp. 245–264.

[27] W.F. Denning, "Telescopic Work for Starlight Evenings", Taylor and Francis, London, 1891, p. 66. Denning's views on the education and instruction of novice astronomers are further explored in Chapter 3.

[28] C.P. Olivier, "Meteors", Williams and Wilkins, Baltimore, 1925.

[29] M. Beech, "The Herschel-Denning Correspondence", *Vistas in Astronomy* 34, 1992, pp. 425–447.

[30] W.F. Denning, "Professor A.S. Herschel, F.R.S", *Nature* 76, 1907, pp. 202–203.

[31] The constraints on orbital dynamics are explained, for example, in J.C. Brandt and R.D. Chapman's "Introduction to Comets", Cambridge Univ. Press, Cambridge, 1981, pp. 61–65.

[32] A summary of the early work on meteor physics is given by E. Öpik's "Physics of Meteor Flight in the Atmosphere", Interscience Publishers, Inc., New York, 1958.

[33] F.A. Lindemann, G.M.B. Dobson, "A Theory of Meteors, and the Density and Temperature of the Outer Atmosphere to Which it Leads", *Proc. Royal Society* 102, 1922, pp. 411–437.

[34] Halley's early discussion on meteor origins are further explored in M. Beech's "Halley's Meteoric Hypothesis," *The Astronomy Quarterly* 7, 1990, pp. 3–18.

[35] W.F. Denning, "Fall of an Aerolite in Mokoia, New Zealand, on November 26, 1908", *Nature* 80, 1909, p. 128. It is not clear what happened to the sample that Denning received. Inquiries to the City Museum at Bristol have revealed that it was not donated to their collection (R.D. Clark, Assistant Curator, Geology, *personal communication*, 1991).

Fireballs and Meteorites

Meteorite Craters Discovered by Means of Examining X-SAR Images—Part I

Roberto Gorelli

We present geologic or geographic structures, assumed to be craters of meteoritic origin, discovered on radar images taken by the X-SAR on board of the Space Shuttle, during missions carried out in April and October 1994.

During the STS 59 and STS 68 Space Shuttle missions in April and October 1994, a new scientific instrument, the X-SAR radar, was taken on the Shuttle for scientific research and practical applications. Its electronic images, not photographs, made possible a great number of scientific discoveries. For some time now, part of these images, with degraded resolution, have been made accessible for public use in an Internet site thanks to *DLR*, a scientific institute specialized in remote sensing. The author, assuming that the available resolution could be sufficient, tried to verify if it were possible to confirm the meteoritic origin of some structures, previously discovered on optical photos taken from satellites, and of other curious structures found on geologic or geographic maps. For some structures, the verification has been positive: X-SAR images have confirmed the hypothesis of their meteoritic origin for some structures, while excluding it for the other ones. During this job, limited and well-finalized, some images erroneously requested to the *DLR* were studied, and some of these images also revealed meteorite craters, never discovered before. These accidental discoveries led the author to examine part of

the approximately 25 000 available images in search of other meteorite craters. The results are beyond expectation: more than 20 geologic or geographic structures with certain, probable or possible meteoritic origin were found.

Naturally, the final word can only be given after a field survey. The recent discoveries by American investigators of a crater of approximately half a mile in diameter in Yemen, a crater of 13 km diameter in South Korea, the Aorounga crater chain in Chad, all of meteoritic origin, and the discovery by *DLR* investigators of a spectacular crater, perhaps more beautiful than the Meteor Crater in Arizona, whose discovery has not been yet made public[1], lead me to think that, even if not all the structures discovered in this study are meteoritic craters, surely a number of them will see meteoritic origin confirmed after being examined in the field.

Here, we present the structures discovered. For each one, we provide all the data obtained from the degraded X-SAR images; more accurate data and particulars are certainly to be found in the full-resolution images, which have not yet been examined. The data include the coordinates of the crater center, the crater diameter, its estimated age, the reliability of the proposed meteoritic origin, and notes of the author.

The crater coordinates, obviously not shown on the legend of the images, have been obtained from the author by means of a particular method, too long to be described in this paper, but the validity of which has been validated on well known meteorite crater images. Although professional geographers would probably propose other methods, the errors on the crater coordinates are less than one arc minute (notice that the coordinates are given in hundredths of degrees). The diameters of the craters have been derived with the same method, which has also been tested on diameters of known craters, from which we have deduced that the error of measurement is less than 10%. The crater ages are only estimates, based on geological and geographic considerations, so for some craters it could be off by even hundreds of millions of years, but, generally speaking, the error margin is between half and double of the proposed age. The reliability of the meteoritic origin has been qualified as "certain," "probable" and "possible." Since no crater has been investigated in the field, none of them can be designated as meteoritic with real certainty, strictly speaking; the qualification "certain" means that the craters show details and characteristics that cannot be attributed to a terrestrial origin. The other two qualifications, "probable" and "possible," indicate only a greater or smaller possibility that the meteoritic origin of the crater concerned will be confirmed. The notes provide all other relevant information.

1. *Crater coordinates*: $\lambda = 15\overset{\circ}{.}65$ E, $\varphi = 31\overset{\circ}{.}30$ N (Libya).

   Diameter: 16.74 km.

   Presumed age: less than 100 million years.

   Reliability: possible.

   Notes: Probably, the structure is not particularly noticeable from the ground, as it was formed at the sea side, where its ejecta formed a cape, today almost invisible due to the presence of coastal lakes.

2. *Crater coordinates*: $\lambda = 33\overset{\circ}{.}97$ E, $\varphi = 17\overset{\circ}{.}11$ N (Sudan).

   Diameter: 60.3 km.

   Presumed age: less than 100 million years.

   Reliability: probable.

   Notes: Discovered some years ago on the photo 01-107-03 taken from Spacelab I, on December 2, 1983, $6^{h}27^{m}$ UT, handled by DFVLR for the ESA agency, where it is clearly visible. It is not so evident on the X-SAR image, because only half of the crater is visible. However, the X-SAR image reveals clearer details than the optical image, and therefore confirms it. It is possible that the area where the crater is situated rose in north-eastern

[1] The author deems it appropriate not to disclose the location of this crater before the discoverers have made a formal announcement.

direction or sank in south-western direction. This geological phenomenon could explain the distinct asymmetry in the appearance of the crater. Since such phenomenon takes place on a long time scale, the crater is probably very old. Towards the SSW, a smaller, less distinct structure is visible, with a diameter of 15–19 km, which may also be a meteorite crater.

3. *Crater coordinates*: $\lambda = 32.^{\circ}75$ E, $\varphi = 18.^{\circ}93$ N (Sudan).
   Diameter: 0.9 km.
   Presumed age: less than 1 million years.
   Reliability: possible.
   Notes: The radar bundle lighting system shows perfectly the ring, higher than the surrounding territory.
4. *Crater coordinates*: $\lambda = 46.^{\circ}64$ E, $\varphi = 21.^{\circ}36$ S (Madagascar).
   Diameter: 0.86 km.
   Presumed age: less than 10 million years.
   Reliability: possible.
   Notes: The smallest of the proposed structures. It does not seem to have caused an appreciable relief outside the ring. It appears broken off towards the NNE.
5. *Crater coordinates*: $\lambda = 46.^{\circ}78$ E, $\varphi = 21.^{\circ}09$ S (Madagascar).
   Diameter: 2.47 km.
   Presumed age: less than 10 million years.
   Reliability: probable.
   Notes: The structure is formed on a very uneven area, and must therefore be very hard to identify from the ground. A view from medium-high altitudes is necessary to bring the crater into evidence.
6. *Crater coordinates*: (Crater A) $\lambda = 104.^{\circ}30$ E, $\varphi = 48.^{\circ}63$ N;
   (Crater B) $\lambda = 104.^{\circ}25$ E, $\varphi = 48.^{\circ}64$ N (Bulgan, Mongolia).
   Diameter: (Crater A) 2.57 km; (Crater B) 2.48 km.
   Presumed age: less than 10 million years.
   Reliability: (Crater A) certain; (Crater B) probable.
   Notes: Crater A is located on a gentle slope of a big massif, and is the perfect example of a meteorite crater, even more so than the famous Arizona Meteor Crater. Crater B is located on the summit of the same massif, and exhibits clearer signs of erosion. The difference of reliability is due to the possibility that the latter crater is a glacial circus. Near the craters, there are one or more less distinct structures that may also be meteorite craters. One of them has a diameter of 1.24 km.
7. *Crater coordinates*: (Crater A) $\lambda = 13.^{\circ}78$ W, $\varphi = 19.^{\circ}38$ N;
   (Crater B) $\lambda = 13.^{\circ}76$ W, $\varphi = 19.^{\circ}34$ N (Mauritania).
   Diameter: (Crater A) 1.32 km; (Crater B) 1.88 km.
   Presumed age: less than 10 million years.
   Reliability: (Crater A) certain; (Crater B) possible.
   Notes: Crater A is almost completely filled up, making it practically invisible from the ground. Its most remarkable characteristic is the deformation of the southern part of the crater rim, which may indicate that it was caused by a meteorite coming from the north, Around the crater, a halo with a diameter of about 2.5 km showing alterations caused by the impact is visible. Crater B is completely filled up; only the rim is visible. It is located between two sand dunes that may have been one dune before the impact. At the limit of visibility, some craters with diameters in the order of hundreds of meters can be distinguished: the presence in Mauritania of craters due to volcanic explosions makes it imperative to check their origin first before jumping to conclusions.

8. *Crater coordinates*: $\lambda = 38\overset{\circ}{.}98$ E, $\varphi = 32\overset{\circ}{.}78$ N (Syrian Desert, Iraq).
   Diameter: 2.82 km.
   Presumed age: less than 50 million years.
   Reliability: possible.
   Notes: The crater is embedded in an annular geological structure of about 7.2 km diameter. If the entire structure is a crater, then the central area with 2.82 km diameter is a drained lake in the center of the crater. This structure is about 40 km WNW of the Al Umchaimin structure also suspected to be a meteorite crater. The Al Umchaimin structure was examined, too. It is probably nearly invisible in the optical photographs from satellites, as it shows no relief. It is clearly found on the radar images, however, because of the ejecta that cover the crater: rays of ejecta can be seen on the image, to the perception limit, in opposite directions with respect to the crater, indicating a SW to NE or inverse trajectory.
9. *Crater coordinates*: $\lambda = 99\overset{\circ}{.}30$ W, $\varphi = 58\overset{\circ}{.}94$ N (Manitoba, Canada).
   Diameter: (external ring) 5.13 km; (internal ring) 3.80 km.
   Presumed age: more than 250 million years.
   Reliability: certain.
   Notes: The crater is invisible from the ground, because it is totally filled up with rocks. Seen from high altitudes, the place shows two nearly complete concentric rings that form two streams almost filled up with water and with a lake with irregular shape in the center. The crater, filled up and covered by rocks of later age, has then reappeared later due to the ablation of the last glaciation ice, which acted in a selective way on rocks of various hardness, making more evident the crater contour and one of the rock layers that had filled it up. This crater is probably nearly invisible in satellite photographs, but shows up clearly in the radar images of the X-SAR, which with its radar directional lighting system can register minimal height differences on the ground. Nearly adjacent and at the limit of visibility, there may be a slightly smaller crater filled up with rocks too, with a diameter of 2.47 km and the center at $\lambda = 99\overset{\circ}{.}55$ W and $\varphi = 58\overset{\circ}{.}94$ N. It shows a ring partially filled by two lakes and a depression filled by a lake at its center; the reliability of this last structure must be qualified as "possible."
10. *Crater coordinates*: $\lambda = 100\overset{\circ}{.}36$ W, $\varphi = 54\overset{\circ}{.}82$ N (Manitoba, Canada).
    Diameter: 4.40 km.
    Presumed age: less than 250 million years.
    Reliability: probable.
    Notes: The crater itself is buried by rock; what is observed from the surface is the incomplete annular contour of its inner rim, filled up with water. The contour must have been dug out by selective ablation of the last glaciation ice.
11. *Crater coordinates*: $\lambda = 112\overset{\circ}{.}91$ W, $\varphi = 32\overset{\circ}{.}38$ N (Arizona, USA).
    Diameter: 1.904×1.71 km.
    Presumed age: less than 1 million years.
    Reliability: possible.
    Notes: It is a very clear crater, without raised edge. The shadow reveals an elliptical shape, elongated in NNW-SSE direction. There is a little lake near the center of the structure. It does not appear to contain even minimal trace of ejecta, which have to fill up partially all meteorite craters on a planetary body with an atmosphere, which may suggest a terrestrial origin for the structure (karst). At the limit of the resolution, holes with a diameter of less than 200 m can be distinguished around the structure.
12. *Crater coordinates*: $\lambda = 27\overset{\circ}{.}10$ E, $\varphi = 22\overset{\circ}{.}87$ N (Lybian Desert, Egypt).
    Diameter: (main crater) 3.59 km; (SSW crater) 0.75 km; (NW crater) 1.04 km.

Presumed age: less than 50 million years.

Reliability: (main crater) probable; (SSW and NW craters) possible.

Notes: This is a very complex and curious geological structure. Its shape resembles an eye looking at the sky: it is composed of a big and perfectly round crater, which, slightly excentric, contains another perfectly round but much smaller crater. Internally this second crater contains a saucer-shaped black surface near its center, which is probable made up of sand or very small stones, with an average diameter of a few centimeters. As a consequence, the surface absorbs the radio waves used by the X-SAR radar, sending a very weak reflected beam, making the surface appear dark, almost black. The presence of ancient volcanoes within a radius of a few hundred kilometers must caution us in assigning a meteoritic origin to this structure. Verification on the ground is therefore very important. It is important to remember that a positive identification of this crater as meteoritic could solve the mystery of the "Kharga Oasis Glass" or "Libyan Desert Glass", natural glass of unknown origin that someone thought to be of impact origin (tektites), although the corresponding crater was never found.

13. *Crater coordinates*: $\lambda = 96^\circ.44$ W, $\varphi = 49^\circ.79$ N (Manitoba, Canada).

    Diameter: 5.74 km.

    Presumed age: less than 5 million years.

    Reliability: certain.

    Notes: The crater is very evident, it shows a raised rim in the south-eastern part, and apparently showed a fairly good depth.

14. *Crater coordinates*: (Crater A) $\lambda = 16^\circ.18$ E, $\varphi = 27^\circ.61$ N;
    (Crater B) $\lambda = 16^\circ.20$ E, $\varphi = 27^\circ.66$ N (Namibia).

    Diameter: (Crater A) 3.77 km; (Crater B) 0.57 km.

    Presumed age: 3.7 ± 0.3 million years.

    Reliability: (Crater A) certain; (Crater B) possible.

    Notes: Crater A is perhaps the most evident of the craters exhibited in this paper, to the extent that the author proposes to name this crater the "Dune Crater". It is at only 15 km from the well known Rotter Kamm Crater, which is of certain meteoritic origin. The proximity of the two craters suggest that both may have originated from the same impact, in which case they have the same age. Dune Crater, the bigger one of the two, is probably the main geological structure caused by this event. The reason that it has been missed previously is probably that it is completely covered by sand, and has a large sand dune within which prevented recognition of the crater shape from the air as well as from the ground. Crater B was discovered by Andrea Pelloni while reading and verifying an earlier draft of this paper. It is located between Dune Crater and Rotter Kamm. We qualified its meteoritic origin as "possible," because its size is near the limit of the resolution.

This overview concludes the first part. The bibliography is included in the second part.

Call for meteor photographs

We are always short of spectacular meteor photographs for the cover of WGN. *If you happen to make such a photograph, do not hesitate to send it in!*

Occasionally, other photographs, such as good photographs of observing groups, may also qualify for the front page. (Ed.)