

THE GENESIS OF CAVE RINGS EXPLAINED USING EMPIRICAL AND EXPERIMENTAL DATA

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Abstract: A cave ring is a faint speleothem consisting in a thin circle on the floor symmetrically surrounding a water drop impact point. Two different mechanisms seem to be responsible for cave ring formation: the drop splash at the floor, for the splash rings, and the ejection of a secondary droplet during the fall, for the fall down rings. A systematic investigation of 67 speleothem rings discovered in five different caves in central Italy was conducted. The data show compatibility with a common nature for all the observed rings. For the observed rings, the hypothesis of a falling secondary droplet origin is confirmed and the hypothesis of a primary drop splash is rejected. The trajectory of a secondary droplet has been measured, and the collected data suggest that the secondary droplets originate from a primary drop breakup at a distance $y_0 = 142.7 \pm 7.2$ cm from the stalactite tip. Assuming this spontaneous breakup hypothesis, the velocities ratio $b = v_y/v_x = 25.5 \pm 1.6$ at the breakup time was measured. Finally, the collected ring data (5-cm- to 50-cm-diameter range) exhibit a negative curvature trajectory. The large departure from a gravity dominant parabolic trajectory suggests other forces, such as air friction or lift force, are at work on the small secondary droplets.

INTRODUCTION

A cave ring is a faint speleothem consisting of a thin circle on the cave floor symmetrically surrounding a water drop impact point. Depending on the water composition and the substrate, both positive or negative³ rings were observed. Focusing on the more commonly occurring positive rings, the measured diameters range from a few centimeters to about two meters, depending on the height of the cave roof and on the formation mechanism. The ring width ranges from a few millimeters to a few centimeters and the surface of the calcite deposition ranges from a barely perceptible roughness to a ring thickness of a few centimeters (Hill and Forti, 1998; Torres Capote et al., 1991; Auler 1993; Montanaro, 1992). Perfectly circular rings are observed on flat floors, but when the floor slope increases, elliptical or elongated rings are observed with the major axis aligned with the dip direction. Formation survival⁴ and visibility of a similar speleothem requires specific characteristics of the floor, such as the absence of strong water flows that could wash out the ring. Moreover, the rings are more easily revealed if a thin mud or dust film is covering a calcitic floor because of the increased contrast between clean and unclean areas.

Two different mechanisms appear to be responsible for cave ring formation. The first mechanism, capable of providing the larger observed rings (Hill and Forti, 1998), results from secondary droplets that are radially ejected

after the primary drop splash on the floor. In this case, the secondary droplet velocity is related to the primary drop velocity at the impact point and is dependant on cave roof height and probably on the drop mass. The maximum bouncing distance of the secondary droplets is obtained when the ejection angle is 45°. The maximum bouncing distance determines the ring radius, and the random ejection direction of secondary droplets is responsible for the whole circle formation (Hill and Forti, 1998). In this article, we refer to rings generated with this mechanism as splash rings.

A different mechanism has been described for some smaller rings in the Grotta del Sorell cave in Sardinia (Montanaro, 1992). In this case, the ring is drawn by the superposition of many secondary droplets, but they are not ejected from the primary drop splash on the floor. In fact, the preliminary measurements of Montanaro showed that the secondary droplets originate near the roof, fall towards the floor, and retain an axial symmetry with respect to the primary drop trajectory. Montanaro postulated that the ejection of a secondary droplet was a result of a spontaneous breakup of the primary droplet after an approximate fall of two meters. The height of the breakup and the horizontal and vertical velocities of the droplet should be exactly constant to ensure a fixed ring radius, and the random ejection direction of the droplet is responsible for the whole circle formation. In the following, we refer to rings generated with this mechanism as fall down rings.

³The presence of negative rings on the gypsum floor at Lechuguilla Cave has been reported by Davis (2000).

⁴The rings can be quickly destroyed if stepped on during the cave exploration, and despite the lack of frequent observations of these speleothems, cave rings should be very common in many dry and richly decorated caves.

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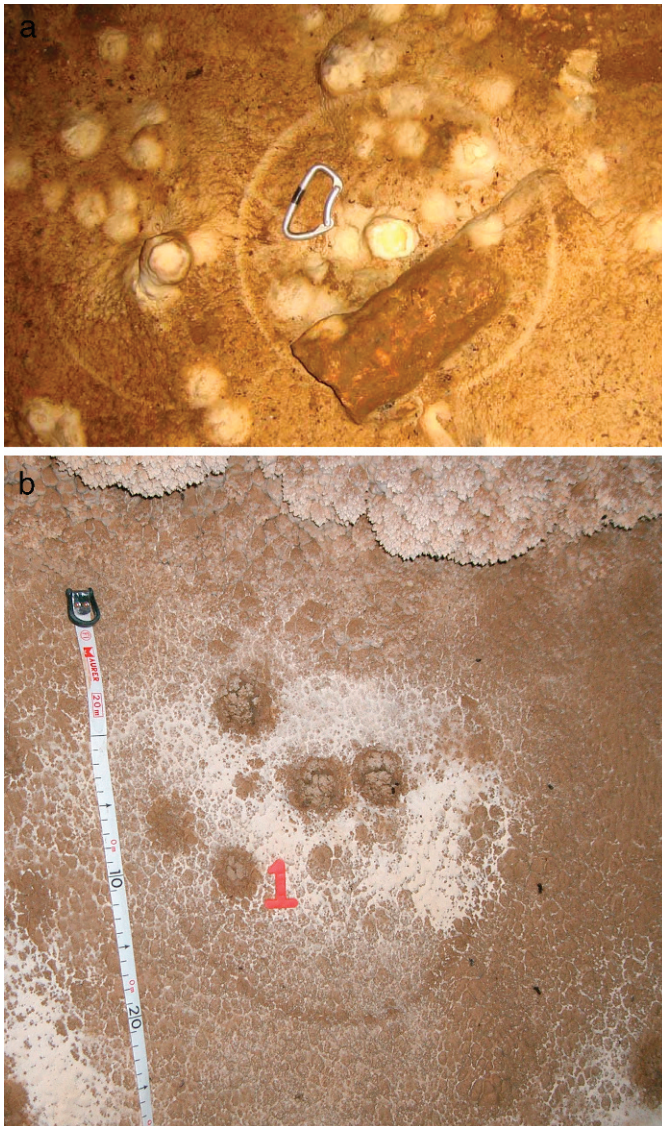


Figure 1. a): The most beautiful rings discovered in the Grotta Imbroglita Cave. b): Example of rings discovered in the dry lake of the Grotta del Secchio Cave.

For both cases, only qualitative results have been reported on the phenomenon. In particular, the second generation mechanism, which assumes the spontaneous breakup hypothesis, is very intriguing from an aerodynamic and fluid-dynamics point of view (see e.g., Joseph et al., 1999). Therefore, cave rings can also act as an ideal laboratory for additional investigations of Montanaro's postulated spontaneous breakup mechanism.

THE MEASURED SAMPLE

After the accidental discovery of some beautiful circles in the Grotta Imbroglita Cave (Fig. 1a), a systematic search for rings in various caves was pursued, providing a relatively large sample set (67 rings) distributed in five

caves in central Italy. Forty-one new rings were discovered in four caves in the Lazio region (all located at a distance less than ~ 100 km from Rome) and five rings were artificially generated in the Grotta Imbroglita Cave (Table 1). Moreover, 21 rings were measured in the Grotta del Sorell Cave located on Sardinia Island. In this cave, more than one hundred rings are present that were previously investigated by Montanaro (1992). Interestingly, all these caves occur in very different karst areas, the caves are of different types, and the cave meteorology of each is dissimilar.

As general features, the observed rings were characterized by a barely perceptible roughness due to the calcite deposit, but were detected by the presence of a thin mud film covering the floor, where they provide a cleaner thin circular corona (Fig. 1a). An exception to this rule is evident in the Grotta del Secchio Cave where some circles have been found at the base of a small dry internal lake (this lake is full during rainy seasons). In this instance, the ring was somewhat darker as compared to the cave floor (Fig. 1b). All the observed rings are associated with a small central stalagmite, and the drop frequency of this primary drop was from ~ 0.1 Hz to less than $\sim 3 \times 10^{-4}$ Hz (e.g., no drops were falling within the one hour frequency of measurements). In addition, clear real-time evidence for a secondary droplet falling on the ring was never obtained during the ring observations.

RING MEASUREMENTS

For all the observed rings, the diameter and the distance from the central stalagmite and the generating stalactite (ring-height) were measured. Elliptical or elongated rings (e.g., rings on tilted cave floors) appear as perfect circles when observed from above so the minimum diameter was considered in the measurements because it is equal to the diameter of the projected circle.

For the case of incomplete circles, the radius from the central stalagmite was measured, which causes additional uncertainties for the correct estimation of the center. However, for all the measured rings, the larger uncertainty is provided by the pointing (and correct guess) of the generating stalactite on the roof. In fact, despite the use of a laser meter coupled to an air-bubble level, the exact targeting of the stalactite tip was, for all practical purposes, impossible, and fluctuations in the measured ring-height on the order of 15–20 cm (typical scale length for stalactites) were likely, as demonstrated by repeated measurements.

ARTIFICIAL RINGS

In order to understand the formation mechanism for the observed rings, some circles were artificially reproduced following the procedure developed by Montanaro (1992). In particular, wooden scaffolding was used in the Grotta Imbroglita Cave, and wooden tablets blackened with soot were placed at various heights over the original rings

Table 1. Cave ring sample distribution.

Cave	Cave Type	Altitude, m	Coordinates	Ring Position	Measured Rings
Grotta Imbroglita ^a	Tectonic cave	690	13°26'34"9 E 41°44'31"0 N	~50 m from entrance and ~-30 m deep	21 and 5 artificial
Pozzo l'Arcaro ^b	Tectonic cave	345	13°17'56"4 E 41°33'01"2 N	~50 m and ~-50 m deep from top entrance	1
Grotta dell'Inferniglio ^c	Active spring	510	13°09'21"6 E 41°53'26"1 N	~30 m from entrance	10
Grotta del Secchio ^d	Relic spring	750	13°08'05" E 42°06'36" N	~200 m from entrance	9
Grotta del Sorell (GEA) ^e	Sea cave	...	08°09'36" E 40°34'24" N	~100 m and +15 m from entrance	21

^a 219La (Mecchia et al., 2003, p. 343). No air circulation.

^b 340La (Mecchia et al., 2003, p. 343). Air circulation at entrances.

^c 21La (Mecchia et al., 2003, p. 343). Completely submerged during rainy seasons.

^d 575A (Mecchia et al., 2003, p. 343). Air circulation in the cave.

^e 1580SA/SS (Montanaro, 1992). Rings already measured by Montanaro.

(Fig. 2a). After about 20 days, in vertical correspondence with an original ring on the cave floor, a new artificial ring was always present. The diameter of this new ring decreased with increasing height of the tablet.

To discriminate a splash ring from a fall down ring, some tablets were placed off center over the central stalagmites, and/or a hole was drilled in the tablets to allow the central drops to reach the cave floor. Therefore, because of the splash ring generating mechanism, no artificial rings were seen on the upper tablets and we were confident the observed circles are not a result of drop splash (Fig. 2b). Finally, for two different tablet heights we noted the formation of an additional and unexpected artificial ring without the corresponding circle on the cave floor. This suggests that the fall down ring mechanism could be common, but particular cave floor characteristics are necessary for ring detection.

DATA ANALYSIS

In order to quantitatively explore the ring features described by Montanaro (1992), all the circles data (ring-height vs. ring-radius) were plotted (Fig. 3a). Data from different caves and origin (natural/artificial) were coded by different markers and/or colors. A clear correlation of ring-height and ring-radius is shown by the data, which implies that the generating mechanism is the same for all the measured rings and that the final ring diameter depends only (or mainly) on the distance of the stalactite tip from its base (e.g., ring-height). It is worth noting that this property should not be expected a priori if, for example, the drop trajectory is dominated by some peculiar characteristics of the stalactite tip, or by drop mass, etc. On the basis of this result it is still puzzling that in the same cave only a few rings may be found among hundreds of stalactites, and it is

not clear what phenomena cause some stalactites to generate rings.

The evidence that the measured circles are fall down rings and that the ring-radius is strongly correlated with the ring-height allows for additional interpretation of the plot in Figure 3a. In fact, because the ring-radius is the distance of the secondary drop impact point from the central stalagmite, the data points in the plot of Figure 3a follow the trajectory of secondary droplets in their motion planes. The parameters associated with the secondary drop trajectory are useful when evaluating the ring generation mechanism. Therefore, the data points have been fitted with a quadratic function

$$y = y_0 + br + ar^2 \quad (1)$$

where, y is the ring-height and r is the ring-radius. The parameters y_0 , b , and a are physically related to some trajectory specifics:

1. $y_0 > 0$ represents the drop breakup distance, while the case of a null y_0 is related to a secondary drop ejected by the stalactite tip (e.g., no spontaneous breakup is necessary).
2. $b = v_y/v_x$ is the ratio of secondary droplet vertical velocity (v_y) over the horizontal velocity (v_x) at the breakup time.
3. a is related to the trajectory curvature and to the forces acting on the falling secondary droplets. In particular, a positive contribution is expected as a result of the force of gravity (see red curve in Fig. 3, a) although it is difficult to reliably evaluate the contribution of air friction (and/or air lift force) because it depends on the specifics of the drop geometry.

The black curve plotted in Figure 3a is the best-fit to all the data points ($\chi^2/\text{dof} = 1.3$). Figure 3b shows the

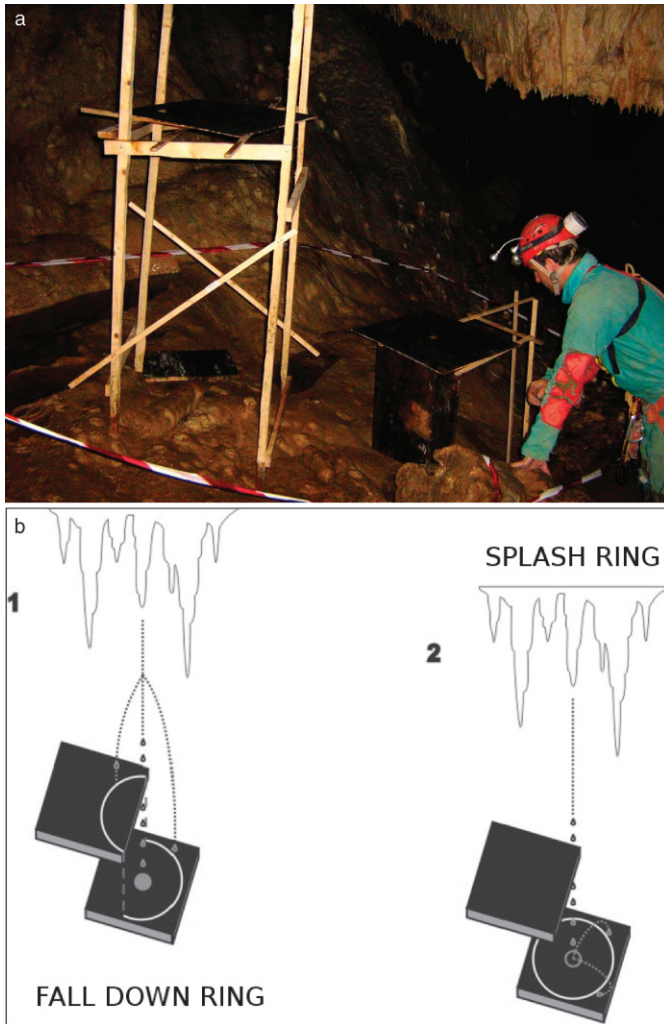


Figure 2. a): wooden scaffolding realized in the Grotta Imbroglita Cave. b): the formation of the ring on the upper tablet excludes the splash ring hypothesis.

distribution of $\Delta h = \text{ring-height} - y_{(\text{best fit})}$ and further demonstrates that the spread in the ring-height measurement (~ 15 cm) is mainly due to the imperfect pointing of the stalactite tips. From Figure 3a, the trajectory parameter values were determined to be $y_0 = 142.7 \pm 7.2$ cm, $b = 25.5 \pm 1.6$, and $a = -0.367 \pm 0.072$ cm $^{-1}$; and therefore, a non-null y_0 was measured with a statistical significance of about 20σ . The value of the curvature related parameter, a , is negative, with a statistical significance of about 5σ . The negative value for the curvature related parameter, a , was unexpected because, according to, Montanaro (1992), the trajectory curvature was described as positive (or it was simply assumed to be positive), as would be expected when gravity force is dominant as in the case for a falling drop (e.g., the red curve in Fig. 3a). However, the presence of a negative curvature was further demonstrated by the same analysis using only the artificial rings. In

Figure 4, the 3σ confidence level allowed space for the y_0 , b , a parameters is reported for the analysis of all data (dark area) or only for the artificial rings data (light area). The star indicates the best fit values of the y_0 , b , a parameters.

PRELIMINARY MASS MEASUREMENTS

With an aim towards detecting evidence of the primary drop related to the ring generating mechanism, a preliminary drop mass measurement was pursued in the Grotta Imbroglita Cave. The mass of the primary drops from stalactites of four different rings was compared with the mass of drops from three stalactites that did not appear related to rings at floor level. Moreover, the drops were collected on the floor, and for ring related drops, the collector opening size was too small for collecting any possible secondary droplets⁵. The mass measurements are summarized in Table 2.

Only the most active stalactites were chosen for measurements. Therefore, relatively high dropping frequencies not representative of the stalactite population were measured. However, the difference between the dropping frequency for the two measured population samples given by

$$\Delta f = f_n - f_r = 0.25 \pm 0.26 \text{ Hz} \quad (2)$$

is still compatible with zero (f_n and f_r are the average dropping frequencies for no-ring drops and ring related drops, respectively).

Regarding the drop mass data, defining m_n and m_r as the average drop mass for no-ring drops and ring related drops, respectively, the difference is given by

$$\Delta m = m_n - m_r = 15.4 \pm 9.5 \text{ mg} \quad (3)$$

which is 1.6σ from zero. This result can be ascribed to statistical fluctuations. However, further primary drop mass data could be useful, in principle, for determining the average mass of the secondary droplets.

DISCUSSION AND CONCLUSIONS

Using the measurements of the 67 rings from the various caves, the qualitative features of the fall down ring speleothem class, originally recognized by Montanaro (1992), were confirmed. In particular, we can confidently reject the hypothesis that the observed circles occur as a result of drop splash at the cave-floor level. Moreover, for the first time, quantitative data were collected and analyzed, and the parameters for the trajectory for the hypothesized secondary droplets generating the rings were determined.

⁵We note that during these measurements, some extremely small droplets were felt on the operator's hands; their position would be comparable with the expected ring-radius, but no quantitative measurements of these droplets were possible for identifying these droplets as the ring generating droplets.

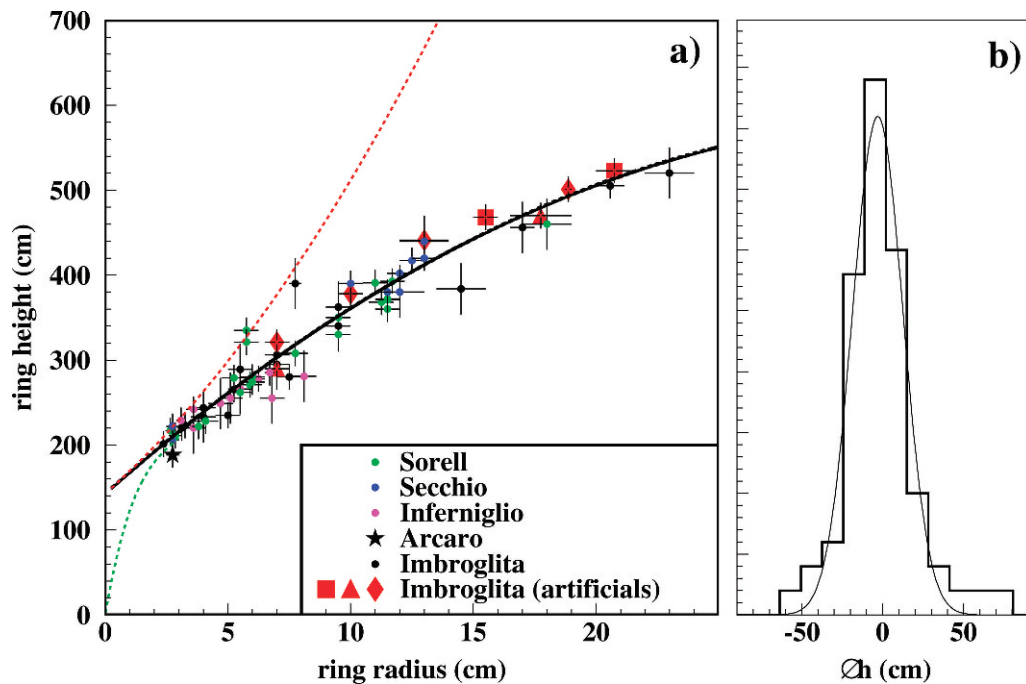


Figure 3. Plot a): Cave rings data points in the plane (ring-height vs. ring-radius); the stalactite tip is placed in the axis origin. The different color/markers refer to data of different caves. The red markers (squares, triangles, diamonds) refer to three different circles that have been artificially regenerated on wooden tablets at various heights from ground. Black curve is the quadratic best fit of all data points. Red dashed curve is the expected behavior assuming the spontaneous drop breakup hypothesis and negligible air friction on the drops. Green dashed curve is an example of possible model where the secondary droplet falls directly from the stalactite tip (e.g., no spontaneous drop breakup is necessary). Plot b): Distribution of Δh . The standard deviation of 15.6 cm obtained from the Gaussian fit is compatible with the spread due to the uncertainty in ring-height measurements.

The results suggest a nonzero value for y_0 (e.g., a spontaneous breakup mechanism of the primary drop should be active as hypothesized by Montanaro (1992)). The measured y_0 value (142.7 ± 7.2 cm) confirms the qualitative indication originally given by Montanaro

(1992) (~ 2 m was given by Montanaro). Assuming the spontaneous breakup hypothesis, the velocities ratio $b = v_y/v_x = 25.5 \pm 1.6$ at the breakup time was determined, which is an interesting parameter for investigation of the hypothesized breakup phenomenon.

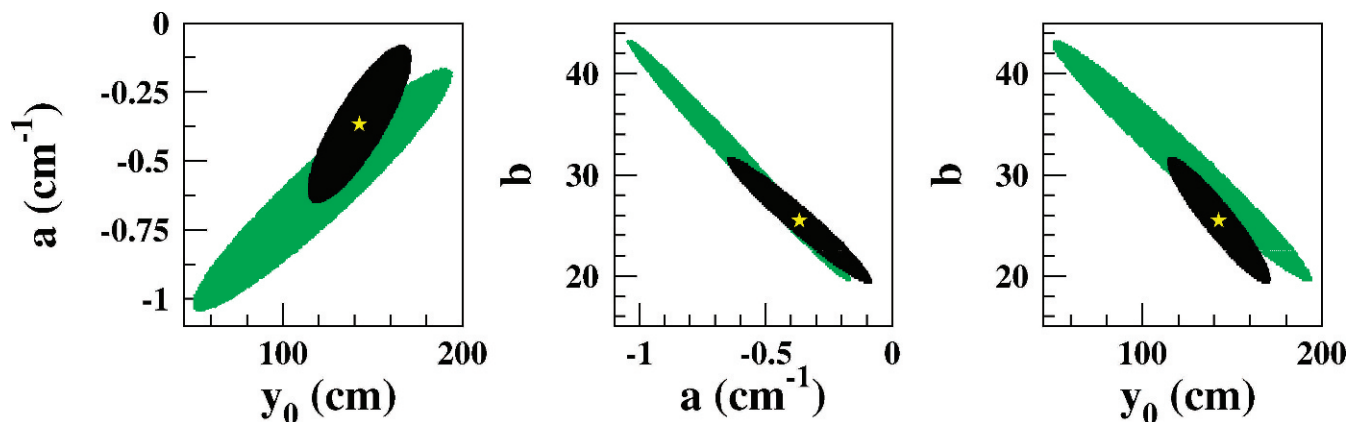


Figure 4. Allowed configurations at 3σ confidence level in the y_0, b, a parameter space for the analysis of all data (dark area) or only of artificial rings data (light area). The compatibility of the configurations allowed by the analysis of artificial rings with the ones allowed by the total data and confirms the trajectory parameter results and, in particular, the presence of a negative curvature. The star indicates the best fit values of the y_0, b, a parameters.

Table 2. Grotta Imbroglita Cave primary drop mass measurements.

Ring I.D.	Collected Drops	Average Drop Frequency, Hz	Average Drop Mass, mg
...	50	0.102 ± 0.004	102 ± 5
...	50	0.147 ± 0.006	93 ± 4
...	100	0.666 ± 0.013	110 ± 3
n. 4	50	0.119 ± 0.005	88 ± 4
n. 12	42	0.028 ± 0.001	97 ± 5
n. 19	40	0.063 ± 0.003	87 ± 5
n. 20	30	0.027 ± 0.002	81 ± 5

A third trajectory parameter $a = -0.367 \pm 0.072 \text{ cm}^{-1}$ was also determined. This parameter is related to the trajectory curvature and the collected data show a negative curvature trajectory. This observed trajectory feature is opposite that of the one described by Montanaro (1992), where a positive curvature was probably assumed as a result of dominance of the force of gravity on the secondary droplets.

The nature of the force driving this negative curvature trajectory is still unclear. However, the large departure from a gravity dominant parabolic trajectory (red curve in Figure 3a) suggests that other forces, such as air friction and/or lift force, are at work on the small secondary droplets. Alternatively, searching for and measurements of the trajectory features for small ring-radii ($\sim 2.5 \text{ cm}$) are very difficult because the primary drop splash on the cave floor would tend to wash out the small rings. Therefore, no data are available at present in this region, and departures from the extrapolated behavior cannot be excluded. This fact implies additional uncertainties on the measured y_0 value (because it is obtained by extrapolating the trajectory at the null radius) and also on the presence of the spontaneous drop breakup phenomenon. This is shown by the green curve in Figure 3a. In this example, an increasing curvature parameter at low ring-radius allows secondary drops falling directly from the stalactite tips. This example of trajectory does not require a spontaneous breakup of the primary drop and, with the present data, similar scenarios cannot be distinguished from previous ones.

Future measurements with a high speed camera should be able, in principle, to yield information about the secondary drop trajectory in this small ring-radius region. However, the final analysis would be much simpler (and cheaper) if very small rings can be found and measured in the future. For example, in Davis (2000), a small negative ring in gypsum is shown in Figure 18; this ring is described (or is assumed) to be a splash ring. A careful observation suggests, however, that the splash ring shown in Davis

(2000) is actually two splash rings that overlap and that are most likely fall down rings. In fact, in the case of a splash ring, a 45° slope of the walls of the central hole and of the ring cuts should be expected. On the contrary, the central hole and the ring cut seem to be practically vertical as expected for fall down rings. The rings in Davis (2000) seem to be very small. Therefore, a further study of their nature and of their parameters (radius and stalactite tip distance) would be very useful as a check on the nature of the hypothesized spontaneous breakup phenomenon (see e.g., Joseph et al., 1999).

As a final conclusion, we recommend all cavers pay attention to the presence of cave rings and we encourage them to develop similar (or better) measurements on newly discovered rings. Particular importance should be directed to the small rings. Lastly, we note that we are available to assist with analyses of any data from new ring samples that may be discovered.

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