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**Supplementary information**

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# **A dense ring of the trans-Neptunian object Quaoar outside its Roche limit**

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# A dense ring of the trans-Neptunian object Quaoar outside its Roche Limit

B. E. Morgado<sup>1,2,3</sup>, B. Sicardy<sup>4</sup>, F. Braga-Ribas<sup>5,2,3</sup>, J. L. Ortiz<sup>6</sup>, H. Salo<sup>7</sup>, F. Vachier<sup>8</sup>, J. Desmars<sup>9,8</sup>, C. L. Pereira<sup>2,3</sup>, P. Santos-Sanz<sup>6</sup>, R. Sfair<sup>10,11</sup>, T. de Santana<sup>4,11</sup>, M. Assafin<sup>1,3</sup>, R. Vieira-Martins<sup>2,1,3</sup>, A. R. Gomes-Júnior<sup>12,11,3</sup>, G. Margoti<sup>5</sup>, V. S. Dhillon<sup>13,14</sup>, E. Fernández-Valenzuela<sup>15</sup>, J. Broughton<sup>16,17</sup>, J. Bradshaw<sup>18</sup>, R. Langersek<sup>19</sup>, G. Benedetti-Rossi<sup>11,3</sup>, D. Souami<sup>20,4,21</sup>, B. J. Holler<sup>22</sup>, M. Kretlow<sup>6,23,24</sup>, R. C. Bouffleur<sup>2,3</sup>, J. I. B. Camargo<sup>2,3</sup>, R. Duffard<sup>6</sup>, W. Beisker<sup>23,24</sup>, N. Morales<sup>6</sup>, J. Lecacheux<sup>4</sup>, F. L. Rommel<sup>2,3</sup>, D. Herald<sup>17</sup>, W. Benz<sup>25,26</sup>, E. Jehin<sup>27</sup>, F. Jankowsky<sup>28</sup>, T. R. Marsh<sup>29</sup>, S. P. Littlefair<sup>13</sup>, G. Bruno<sup>30</sup>, I. Pagano<sup>30</sup>, A. Brandeker<sup>31</sup>, A. Collier-Cameron<sup>32</sup>, H. G. Florén<sup>31</sup>, N. Hara<sup>33</sup>, G. Olofsson<sup>31</sup>, T. G. Wilson<sup>32</sup>, Z. Benkhaldoun<sup>34</sup>, R. Busutil<sup>35</sup>, A. Burdanov<sup>36</sup>, M. Ferrais<sup>37</sup>, D. Gault<sup>17</sup>, M. Gillon<sup>38</sup>, W. Hanna<sup>17</sup>, S. Kerr<sup>17,39</sup>, U. Kolb<sup>35</sup>, P. Nosworthy<sup>17</sup>, D. Sebastian<sup>40</sup>, C. Snodgrass<sup>41</sup>, J. P. Teng<sup>42</sup>, J. de Wit<sup>36</sup>

## Supplementary Information Guide

**Supplementary Table 1 | Circumstances of observations.** Table with the information about each observational station presented in this paper. It contains the geographical coordinates (latitude, longitude and altitude), instruments and data characteristics. <sup>a</sup> The first status is for the detection before closest approach and the second is for after it. Unprobed, means that the observation do not cover the region where the ring is expected to be seen. We highlight that the negative detections should be evaluated together with the S/N and the temporal resolution. <sup>b</sup> Central wavelengths are  $g_s$ : 0.48  $\mu\text{m}$ ,  $r_s$ : 0.62  $\mu\text{m}$ ,  $i_s$ : 0.76  $\mu\text{m}$ ,  $z_s$ : 0.91  $\mu\text{m}$ . <sup>c</sup> The RMS of the light curve's decreases with wavelength with the following values in each band of  $g_s$ : 0.117,  $r_s$ : 0.044,  $i_s$ : 0.037,  $z_s$ : 0.036. <sup>d</sup> See details about the CHEOPS space telescope observations in ref<sup>31</sup> – Morgado, B. E. et al. The stellar occultation by the trans-Neptunian object (50000) Quaoar observed by the ESA CHEOPS space telescope. *Astron. Astrophys.*, 664, L15 (2022).

**Supplementary Figure 1 | The ring detection in each light curve.** The observed flux (black points) and the model (red line) vs. time relative to the observer closest approach. Panel (a): general view of the light curve obtained at the HESS station on 02 September 2018 with closest approach time of 18:16:10.895 UTC, note that no data were acquired after the closest approach around the expected ring detection (blue shaded regions). Panel (b): enlargement of the overlying blue shaded region for the same observer. Panel (c): Ring detections of 11 June 2020, by CHEOPS space telescope light curve (closest approach time at 16:27:25.662 UTC). Panel (d) and (e): enlargement of the overlying blue shaded region for the same observer. Panels (f) contains the light curve observed at Mount Carbine by J. Broughton (closest approach time at 16:30:51.615 UTC) for the same event. Panel (g): enlargement of the overlying blue shaded region for the same observer. Panel (h), (i) and (j): The ring detection of 27 August 2021, the light curve observed in Samford Valley (closest approach time at 10:59:00.528 UTC), and its enlargements. Panels (k), (l) and (m): the light curve observed in Reedy Creek (closest approach time at 10:59:00.096 UTC), and its enlargements. Both light curves were obtained by citizen astronomers, the first by J. Bradshaw and the second by J. Broughton. A third, simultaneous detection is displayed in Figure 1, panels (d), (e) and (f).

**Supplementary Data file | Source Data for Supplementary Figure 1.** Stellar occultation light curves for each occultation that were presented in Supplementary Figure 1. Each sheet

contains the light curve of one observer, the label of each is the same as in Supplementary Figure 1. The first column contains the time in Julian Date (UTC); The second column has the observed normalized flux; the third column contains the best-fitted modeled flux.

## Supplementary Information

Supplementary Table 1 - Circumstances of observations.

| Site                     | Longitude       | Observers      | Telescope aperture               | Exposure time | Light curve                  |
|--------------------------|-----------------|----------------|----------------------------------|---------------|------------------------------|
| Ring status <sup>a</sup> | Latitude        |                | Detector                         | Cycle time    | RMS (flux)                   |
|                          | Altitude        |                | Filter                           | (s)           |                              |
| <b>02 September 2018</b> |                 |                |                                  |               |                              |
| Les Makes                | 55° 24' 36.3" E | S. Perrigault  | 60 cm                            | 0.040         | 0.304                        |
| La Réunion               | 21° 11' 56.1" S | J. P. Teng     | Watec 910HX                      | 0.040         |                              |
| Unprobed – Negative      | 990 m           |                | Clear                            |               |                              |
| HESS – Khomas            | 16° 30' 06.9" E | F. Jankowsky   | 75 cm                            | 0.095         | 0.052                        |
| Namibia                  | 23° 16' 16.6" S |                | DU888BV                          | 0.095         |                              |
| Positive – Unprobed      | 1800 m          |                | Clear                            |               |                              |
| Upington                 | 21° 01' 31.6" E | M. Kretlow     | 25.4 cm                          | 0.500         | 0.056                        |
| South Africa             | 28° 03' 35.2" S |                | Raptor EM247                     | 0.500         |                              |
| Unprobed – Unprobed      | 870 m           |                | Clear                            |               |                              |
| <b>05 June 2019</b>      |                 |                |                                  |               |                              |
| PIRATE Mark III          | 16° 30' 36.7" W | R. Busuttil    | 42.5 cm                          | 8.00          | 0.231                        |
| Tenerife                 | 28° 17' 57.3" N | U. Kolb        | FLI Proline                      | 11.66         |                              |
| Negative – Negative      | 2390 m          | C. Snodgrass   | Clear                            |               |                              |
| Artemis                  | 16° 30' 38.0" W | D. Sebastian   | 100 cm                           | 2.50          | 0.039                        |
| Tenerife                 | 28° 18' 04.0" N | A. Burdanov    | Andor Ikon                       | 3.78          |                              |
| Negative – Negative      | 2390 m          | J. de Wit      | Clear                            |               |                              |
| GTC                      | 17° 53' 30.2" W | V. S. Dhillon  | 1040 cm                          | 0.130         | 0.117 – 0.036 <sup>(c)</sup> |
| La Palma                 | 28° 45' 21.6" N | T. R. Marsh    | HiPERCAM                         | 0.135         |                              |
| Positive – Positive      | 2270 m          |                | $g_s r_s i_s z_s$ <sup>(b)</sup> |               |                              |
| Liverpool                | 17° 52' 45.1" W | P. Santos-Sanz | 200 cm                           | 0.60          | 0.221                        |
| La Palma                 | 28° 45' 44.5" N | J. L. Ortiz    | EEV ANDOR                        | 0.63          |                              |
| Negative – Negative      | 2320 m          | N. Morales     | IR720                            |               |                              |
| TRAPPIST-North           | 07° 51' 57.0" W | E. Jehin       | 60 cm                            | 5.00          | 0.116                        |
| Morocco                  | 31° 12' 22.0" N | Z. Benkhaldoun | Andor IKONL                      | 5.99          |                              |
| Negative – Negative      | 2720 m          |                | Clear                            |               |                              |

<sup>a</sup> The first status is for the detection before closest approach and the seconds is for after it. Unprobed, means that the observation do not cover the region where the ring is expected to be seen. We highlight that the negative detections should be evaluated together with the S/N and the temporal resolution.

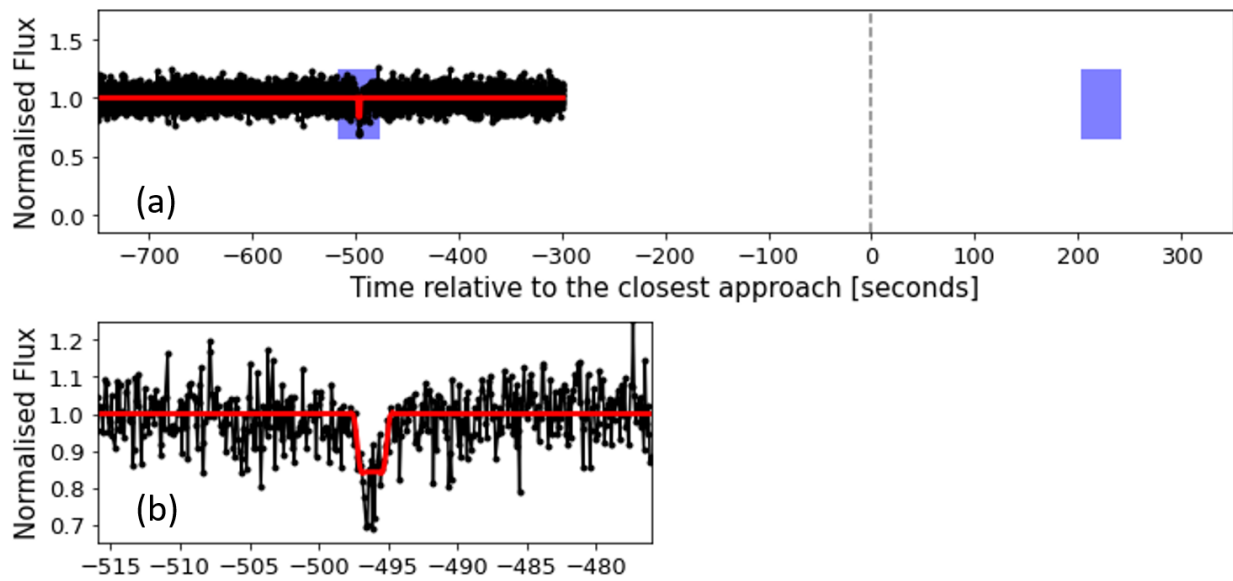
<sup>b</sup> Central wavelengths are  $g_s$ : 0.48  $\mu\text{m}$ ,  $r_s$ : 0.62  $\mu\text{m}$ ,  $i_s$ : 0.76  $\mu\text{m}$ ,  $z_s$ : 0.91  $\mu\text{m}$ .

<sup>c</sup> The RMS of the light curve's decreases with wavelength with the following values in each band of  $g_s$ : 0.117,  $r_s$ : 0.044,  $i_s$ : 0.037,  $z_s$ : 0.036.

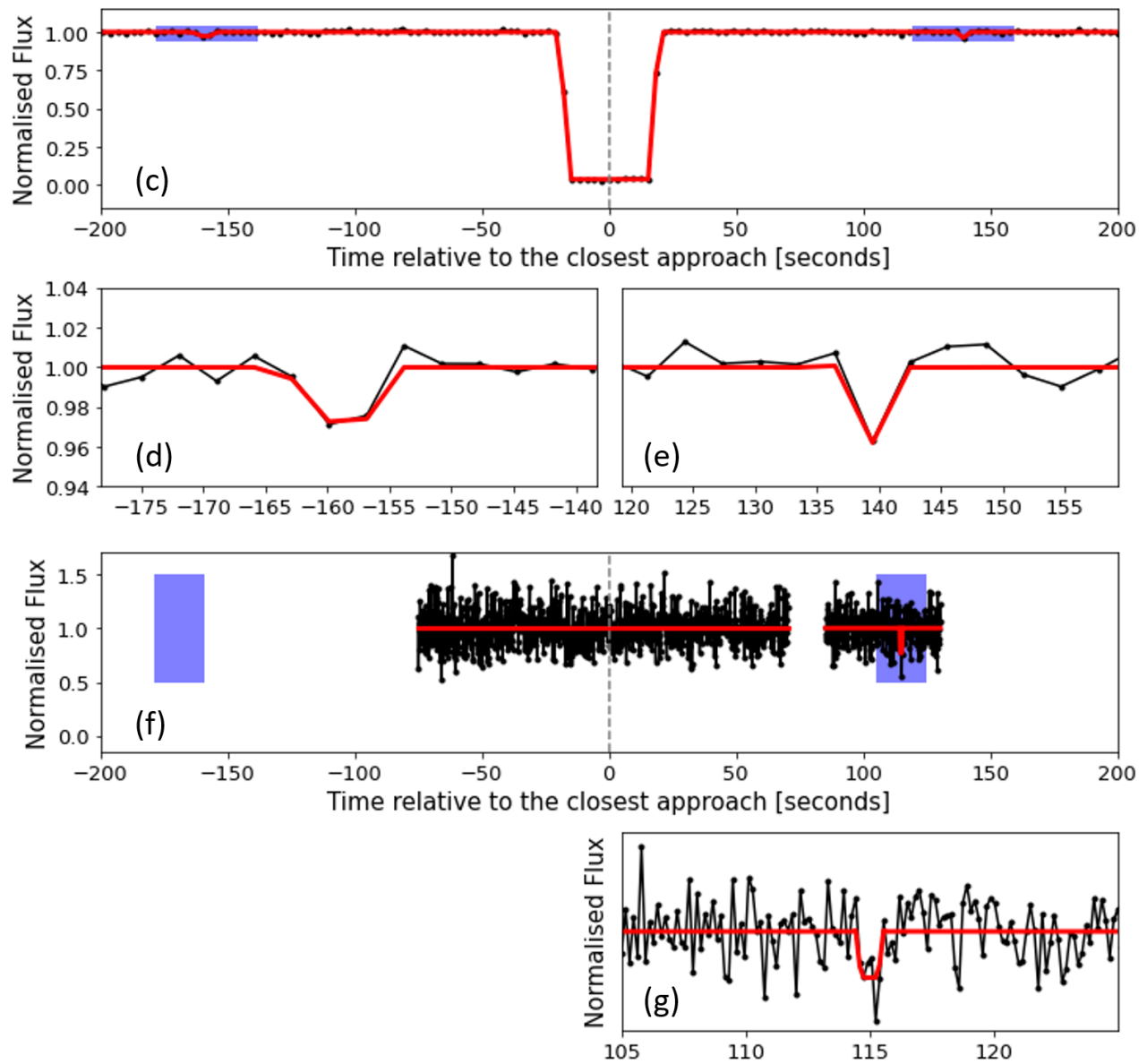
Supplementary Table 1 [Cont.] - Circumstances of observations.

| Site                  | Longitude            | Observers     | Telescope aperture    | Exposure time     | Light curve |
|-----------------------|----------------------|---------------|-----------------------|-------------------|-------------|
| Ring status           | Latitude<br>Altitude |               | Detector<br>Filter    | Cycle time<br>(s) | RMS (flux)  |
| <b>11 June 2020</b>   |                      |               |                       |                   |             |
| ESA CHEOPS            | (d)                  | CHEOPS's team | 32 cm                 | 3.000             | 0.008       |
| Positive – Positive   |                      |               | Teledyne CCD<br>Clear | 3.024             |             |
| Mount Carbine         | 144° 52' 29.4" E     | J. Broughton  | 25 cm                 | 0.160             | 0.147       |
| Australia             | 16° 27' 58.7" S      |               | Night Eagle           | 0.160             |             |
| Unprobed – Positive   | 57 m                 |               | Clear                 |                   |             |
| <b>27 August 2021</b> |                      |               |                       |                   |             |
| Glenlee               | 150° 30' 01.6" E     | S. Kerr       | 30.4 cm               | 0.32              | 0.13        |
| Australia             | 23° 16' 10.1" S      |               | Watec 910BD           | 0.32              |             |
| Unprobed – Unprobed   | 53 m                 |               | Clear                 |                   |             |
| Samford Valley        | 152° 50' 53.2" E     | J. Bradshaw   | 35.6 cm               | 0.25              | 0.11        |
| Australia             | 27° 22' 07.0" S      |               | ASI ZWO174MM          | 0.25              |             |
| Positive – Negative   | 80 m                 |               | Clear                 |                   |             |
| Algerster             | 153° 02' 14.0" E     | R. Langersek  | 28.0 cm               | 0.50              | 0.15        |
| Australia             | 27° 36' 46.0" S      |               | ASI-174MM PRO         | 0.50              |             |
| Positive – Negative   | 46 m                 |               | Clear                 |                   |             |
| Reedy Creek           | 153° 23' 52.9" E     | J. Broughton  | 51 cm                 | 0.25              | 0.18        |
| Australia             | 28° 06' 30.4" S      |               | QHY174-GPS            | 0.25              |             |
| Positive – Negative   | 66 m                 |               | Clear                 |                   |             |
| Hawkesbury Heights    | 150° 38' 27.9" E     | D. Gault      | 30.0 cm               | 0.32              | 0.14        |
| Australia             | 33° 39' 51.9" S      |               | Watec WT-910BD        | 0.32              |             |
| Unprobed – Negative   | 273 m                |               | Clear                 |                   |             |
| Hazelbrook            | 150° 27' 06.5" E     | P. Nosworthy  | 28.0 cm               | 0.32              | 0.15        |
| Australia             | 33° 42' 26.6" S      |               | Watec 910BD           | 0.32              |             |
| Unprobed – Negative   | 648 m                |               | Clear                 |                   |             |
| Yass                  | 148° 58' 35.06" E    | W. Hanna      | 50.8 cm               | 0.25              | 0.13        |
| Australia             | 34° 51' 50.89" S     |               | QHY174M-GPS           | 0.25              |             |
| Negative – Negative   | 536 m                |               | Clear                 |                   |             |
| Murrumbateman         | 148° 59' 56.0" E     | D. Herald     | 40.0 cm               | 0.16              | 0.17        |
| Australia             | 34° 57' 31.3" S      |               | Watec 910BD           | 0.16              |             |
| Unprobed – Negative   | 596 m                |               | Clear                 |                   |             |

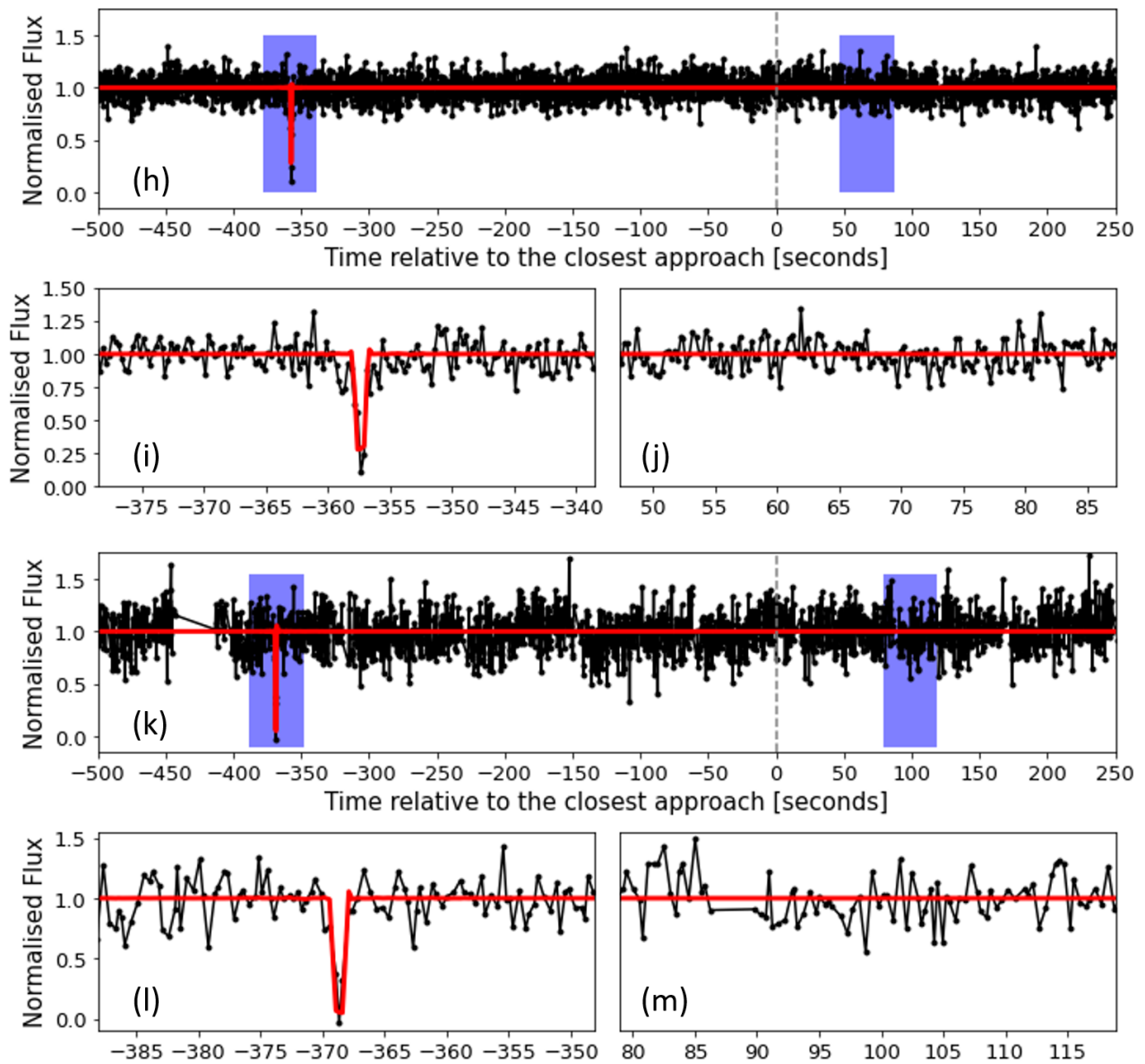
<sup>d</sup> See details about the CHEOPS space telescope observations in ref<sup>31</sup>.



**Supplementary Figure 1 | The ring detection of 02 September 2018.** The observed flux (black points) and the model (red line) vs. time relative to the observer closest approach (18:16:10.895 UTC) at the HESS station on 02 September 2018. Panel a: general view of the light curve, note that no data were acquired after the closest approach around the expected ring detection (blue shaded regions). Panel b: enlargement of the overlying blue shaded region.



**Supplementary Figure 1 [Cont.] | Ring detections of 11 June 2020.** Panels c, d and e: the CHEOPS space telescope light curve (closest approach time at 16:27:25.662 UTC). Panels f and g: the light curve observed at Mount Carbine by J. Broughton (closest approach time at 16:30:51.615 UTC).



**Supplementary Figure 1 [Cont.] | The ring detection of 27 August 2021.** Panels h, i and j: the light curve observed in Samford Valley (closest approach time at 10:59:00.528 UTC). Panels k, l and m: the light curve observed in Reedy Creek (closest approach time at 10:59:00.096 UTC). Both light curve were obtained by citizen astronomers, the first by J. Bradshaw and the second by J. Broughton. A third, simultaneous detection is displayed in Fig. 1, panels d, e and f.