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A Search for Objects near the Earth–Moon Lagrangian Points

FRANCISCO VALDES*,†

Kitt Peak National Observatory, P.O. Box 26732, Tucson, Arizona 85726

AND

ROBERT A. FREITAS, JR.†

Xenology Research Institute, 8256 Scottsdale Drive, Sacramento, California 95828

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A photographic search of the five Earth–Moon Lagrangian positions included the solar-synchronized positions in the stable L4/L5 libration orbits, the potentially stable nonplanar orbits near L1/L2, Earth–Moon L3, and also L2 in the Sun–Earth system. Observations using the 61-cm Burrell Schmidt telescope at the Warner and Swasey Observatory, Kitt Peak Station, spanned 60° along the lunar orbital plane × 5° around Earth–Moon L5, 48° × 5° around L4, 25° × 13° around L3, 15° × 24° around the Moon (L1/L2), and 14° × 14° around Sun–Earth L2. Limiting magnitude for the detection of libration objects near L3, L4, and L5 was 17–19th magnitude, 10–18th magnitude for L1/L2 plates, and 14–16th magnitude for Sun–Earth L2. No natural or artificial objects were found. An automated search of selected priority plates was attempted using the Faint Object Classification and Analysis System (FOCAS) software package.

This paper reports the results of a systematic search of the five Earth–Moon libration positions, as well as Sun–Earth L2, for natural or artificial bodies that might be trapped there. The primary search objective was the investigation of Earth–Moon L4 and L5 and the associated libration orbits and stable phases (Freitas and Valdes, 1980). In addition, we searched for objects based on the potential existence of stable nonplanar "halo" orbits at L1 and L2 in the Earth–Moon system recently discovered by Breakwell and Brown (1979), although the inclusion of lunar eccentricity to the theory appears to ruin the stability. Furthermore, the possibility of related orbits of stability in the vicinity of L3 cannot yet be ruled out on theoretical grounds (Breakwell, 1980, personal communication).

Lagrangian satellite searches may be useful in detecting captured asteroidal bodies or impact ejecta from the lunar surface—unique and accessible material for astrogeological study which could also confirm theoretical predictions in the four-body problem in celestial mechanics. It is also of practical interest to learn whether the stable libration orbits are clear of large obstacles as these positions may come increasingly into use for global telecommunication satellite systems and solar deep-space telemetry networks, space manufacturing facilities utilizing lunar or asteroidal raw materials, large optical and radio telescope arrays, and as part of a comprehensive SETI (Search for Extraterrestrial Intelligence) search for possible alien artifacts in the Solar System (Freitas, 1980).

The current observational status of the triangular libration orbits and L4/L5 is sporadic with limits of 12–14th magnitude

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† Visiting Astronomer at Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation. Observations made with the Burrell Schmidt of the Warner and Swasey Observatory, Case Western Reserve University.

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(Freitas and Valdes, 1980), and the existence of material at these points is still controversial after almost 20 years. No searches for material at Earth–Moon L3 have been reported in the literature. The lunar halo survey near Earth–Moon L1/L2 involves an investigation of the same orbital space examined during previous searches for selenocentric satellites. The best modern effort was by Tombaugh *et al.* (1959), who achieved a limit of 11–12th magnitude in the region encompassing the L1/L2 halo orbits and 13–14th magnitude for most of the rest of the lunar satellite environment. No searches for discrete objects fainter than 14th magnitude near Sun–Earth L2 have been reported in the literature.

OBSERVING PROGRAM

The observing program, with the major goal of obtaining maximum sensitivity to discrete objects in the lunar orbital plane, pursued five distinct objectives as follows.

Earth–Moon L4/L5 Libration Orbit Objects. Our highest priority was to obtain pairs (tracked and sidereal) of plates at the unique solar-synchronized stable phases in the L4/L5 libration orbits. The telescope was driven to track the predicted stable libration orbital positions computed by the methods described in Freitas and Valdes (1980). Previous observers (e.g., Bruman, 1969) have sometimes erred drastically by using a simple 1/6 Moon phase formula and then neglecting to take account of lunar orbital eccentricity and of the fact that each lunar ephemeris tabulated in the Nautical Almanac incorporates the heliocentric motion of the observer, all of which can cause pointing inaccuracies in excess of 10°. Though the Lagrangian points L4 and L5 themselves are predicted to be dynamically unstable, a third plate pair was taken at both L4 and L5 tracked at the lunar rate. Each plate was a sky-limited exposure of 30 min. This includes a declination offset for nonsidereal plates after 15 min to create a double pattern to aid identification of candidate images near the plate limit.

Earth–Moon L4/L5 Libration Orbit Survey. The degree of stability and the mechanics of trapping objects in precisely the theoretical libration orbit and phase is unknown. Oscillations around the ideal stable locations (in the Earth–Moon plane) are likely for natural objects injected into such orbits with arbitrary initial conditions, in which case possible trapped bodies may deviate significantly from the solar-synchronized positions. Also, the extent of out-of-plane motion is thought to be small (a few degrees or less; Roosen *et al.*, 1967; Schechter, 1968; Schutz and Tapley, 1970), but is, at present, undetermined by reliable theoretical computations. Consequently, a series of plates spanning more than the entire 45° libration orbit regions with 0.5° overlap were taken tracked at the lunar rate. The lunar rate was chosen instead of the sidereal to maximize asteroid signatures on the plate, and 30-min exposures gave a sky brightness consistent with the L4/L5 stable phase object plates. The wide Schmidt field produced a 5° swath (in declination) for detecting objects librating vertically about the lunar orbital plane, and the surveys provided coverage of 55° for L5 and 48° for L4 along the plane (Fig. 1). Survey plates on successive nights were overlapped to compensate for possible diurnal object movement.

Earth–Moon L3 Survey. The ephemeris for L3 was computed as a position 180° from the Moon along the lunar orbital plane. A lunar/sidereal rate plate pair was taken at L3, followed by an L3-centered nine-plate survey grid with 0.5° overlap and 30-min exposures with 15-min declination offsets. Time permitted an additional nine-plate survey grid contiguous with the first, to the west. The survey covered a field of 25° (RA) × 13° (Dec).

Earth–Moon L1/L2/Lunar Survey. The families of quasi-stable halo orbits around Earth–Moon L1/L2 remain within 6° east and west (RA) and 12° north and south

(Dec) of the center of the lunar disk (Breakwell and Brown, 1979). A rectangular survey grid with 0.5° overlap was photographed using sidereal-tracked, sky-limited 5-min exposures for all plates except the four nearest the lunar disk, which received 2-min exposures and whose inside edges lay 1° from the lunar limb. This procedure yielded a 15° × 24° pattern, 100% of the expected halo orbital region but only about 50% of the possible selenocentric orbital space.

Sun–Earth L2 Survey. Sun–Earth L2 was included in the present survey because its distance from Earth is only four times that of the Moon and thus was the only remaining reasonable target for terrestrial-based Schmidt telescope searches for small libration objects. The position of L2 was taken as collinear with the Sun and the Earth–Moon barycenter (Farquhar, 1970). A rectangular nine-plate survey grid was photographed centered on L2, using 0.5° overlap and 30-min sidereal-tracked exposures producing a 14° × 14° pattern.

The choice of observing time was dictated by a number of factors which served to maximize the probability of detection of faint libration objects with known or anticipated orbital characteristics. To obtain the maximum reflected brightness from bodies trapped near L4 and L5 the following conditions were satisfied: (1) end of astronomical twilight; (2) end of lunar twilight; (3) maximum lunar declination for a minimum zenith angle for L4 or L5; (4) maximum elongation angle of solar-synchronized objects; (5) minimum reflection angle ensuring "full" phase of possible targets; (6) maximum distance from the Milky Way background for L4 and L5; and (7) maximum post-moonset (L4) or pre-moonrise (L5) observing time. For libration orbit objects the best compromise between requirements (5) and (7) places the Moon no more than 95° (7.4 days lunar phase) from the Sun. Hence a 4-day observation schedule is best completed over the lunar-phase Days 5–8 for L4 and Days 21–24 for L5.

Consistent with these criteria, a total of 137 plates were taken during 26 February–1 March 1981, 18–23 December 1981 and 26 February–3 March 1982 using the 61-cm Burrell Schmidt telescope at the Warner and Swasey Observatory, Kitt Peak Station. All were 196 × 196 mm IIIaF unfiltered plates, baked in 2% hydrogen-forming gas at 65°C to optimize sensitivity before exposure, and developed with machine agitation for 5 min in D-19. One test plate was taken at the beginning of each run to calibrate the nonsidereal tracking drive rate.

RESULTS AND CONCLUSIONS

Each plate was scanned independently by both observers for faint asteroid signatures, using a stereoscopic microscope and light table. Nonsidereal plates of the six pairs taken near L4/L5 were examined for several hours each at high magnification, and the remaining plates were scanned at lower magnification for the expected double image of a potential Lagrangian object. The results were negative. Most candidate images could be ruled out at once as emulsion defects based on size, doublet position

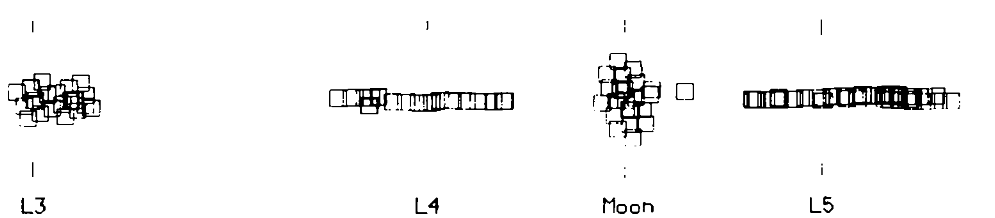

FIG. 1. Schematic plot showing positions of plates taken along the lunar orbital plane. Each box is 5° square.

angle, separation distance, or shape, and all remaining suspect image pairs were eliminated by comparison with overlapping plate fields.

Automated searching of the six nonsidereal priority plates consisting of L4, L5, and each of their two stable synodic libration orbit positions was attempted using the Faint Object Classification and Analysis System (FOCAS; Jarvis and Tyson, 1980; Valdes, 1982) developed at Bell Laboratories. Each plate was digitized to 2 arcsec resolution on the Kitt Peak PDS Scanning Densitometer, after which the image data were processed by finding continguous pixels with densities above a threshold relative to local sky. These detections formed a catalog from which the signature of possible candidates could be automatically selected. The starting catalog for the plate with the lowest rms sky noise, consisting of 3000 objects, was culled by selecting all paired images having nearest-point separations within ± 5 pixels of the declination offset distance and within $\pm 80°$ of the position angle of the declination offset segment, having apparent brightness differing by at most 1 magnitude, and having lengths less than that of a 15-min star trail. This sorting reduced the size of the plate catalog to about two dozen pairs, which were then carefully examined by eye. Of the test image pairs inserted at random into the data 93% were detected by FOCAS, thus verifying the proper operation of the software package in the present application. Unfortunately each of the remaining exposures was taken in a more crowded field so virtually the entire plate had trailed images. The lack of a sufficient sky background rendered these photographs unsuitable for further processing, pointing up the need for uncrowded fields if systems like FOCAS are employed in future observations of this kind.

To provide an accurate magnitude calibration, all sidereal fields were located on the Palomar Sky Survey plates. Image diameters of a dozen stars near the plate limit were measured for each sidereal field using the KPNO two-axis Grant machine. These sizes were compared with those tabulated by King and Raff (1977) for the red Sky Survey plates (which most closely match IIIaF response) to determine limiting magnitudes at various times during each night of every observing run. The magnitude limit for the Earth-Moon L1/L2 plates for objects moving near the sidereal rate ranged from 12–15th magnitude within 2–4° of the Moon to 17–18th magnitude beyond about 8° from the lunar disk, corresponding roughly to objects 3–30 m in size having lunar surface albedo. For objects moving closer to the lunar rate, 1–2 magnitudes would be lost to image trailing giving a range of 10–16th magnitude, approximately doubling the minimum sizes of detectable objects. The limit for the Sun–Earth L2 plates was 14–16th magnitude (depending on image trailing), an object size of about 20–40 m at lunar albedo. The limit for libration orbit objects, surveys at Earth–Moon L4/L5, and L3 was 17–19th magnitude, corresponding to a hypothetical object size of 1–3 m at lunar albedo.

No discrete Lagrangian objects were found in this search to the limits given, although numerous Belt asteroids were detected on the Sun–Earth L2 plates. The survey was not sensitive to diffuse sources and thus does not exclude micrometeorite population enhancements in the Lagrangian regions.

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