LONEOS Project Description
Ed Tedesco 24 December 2023 / Revised 14 May 2024

Abstract

This document summarizes information regarding the LONEOS project obtained from three abstracts, three refereed papers, two National Research Council (NRC) reports, an unpublished manuscript, and inferred from the headers of the LONEOS Flexible Image Transport System (FITS) images.

1. INTRODUCTION

There are few publications describing the LONEOS project in any detail. Searches for documentation of any kind yielded little of substance regarding the telescope, camera, image acquisition software, data processing, details of how the program was conducted, or the format of the various data files (primarily FITS images) produced.

Both the PI and Project Manager of LONEOS have retired and were not available to provide any details regarding the existing data or how it was obtained. Thus, what we know about the project comes from three abstracts (Bowell, *et al*., 1995; Koehn and Bowell, 1999, 2000), three non-project-authored publications that mention it (Diercks, *et al*., 1995; Stokes, Evans, and Larson, 2002; Miceli, *et al*., 2008), two NRC reports (1998 and 2009), and an (as far-as-we-know) unpublished manuscript giving a high-level overview of the project beginning in 1992 and continuing to 2008 (Bowell, *et al*., 2008), plus what I could glean from the image headers, and questions answered by the project's still active (as of 2023) principal observer (Brian Skiff).

See loneos_data_acquisition.pdf for how, and in what formats, the LONEOS data (primarily images) were obtained, loneos_processing_details.pdf for how they were processed into images with World Coordinate System (WCS) information added, and loneos_archive_directory_structure.pdf for details on the archive's directory structure.

2. LONEOS PROGRAM LITERATURE

Two NRC reports, describing Near-Earth Object Surveys in general, have the following to say about the LONEOS program:

"*The LONEOS system, which began test observations in 1997, has an instantaneous field of view of 3° × 3° and an expected threshold of detection of about V magnitude 19.5. In full operation, LONEOS will be capable of covering the entire accessible sky (about 15,000 degree*^{2}*) each month to detect all observable asteroids to apparent magnitude 19.5. …".* (NRC, 1998). This is not true. It describes the survey conducted using the second (of two) cameras from which we have images[1] taken between 2000/02/04 and 2008/03/01 and which is referred to herein as the LONEOS-II survey. This was preceded by a survey (LONEOS-I) from which we have images obtained between 1998/04/25 and 2000/01/11. The difference between these two surveys is discussed below.

"*The project, funded by NASA, began in 1993 and concluded at the end of February 2008. LONEOS discovered 288 NEOs.*" (NRC, 2009).

The LONEOS-I images we received consisted of images obtained between 1998/04/25 and 2000/01/11 and those from LONEOS-II had images obtained between 2000/02/04 and 2008/03/01. The period from 1993 to 1998/04/24 was devoted to development of the cameras and telescope used once the surveys commenced.

The first document that we know of that mentions LONEOS is a Bowell, *et al*. (1995) abstract. This describes the under-development system as: "… *a 58-cm f/1.91 Schmidt telescope, a CCD camera containing two Loral 2048x2048 chips (eventually two 2048x4096 chips), a Silicon Graphics IRIS 4D/220GTX computer containing six processors, and other computers*."

---

[1] The phrase "from which we have images" is used to differentiate between the images we were able to acquire and the larger number that were actually obtained in the surveys but an unknown number of which were lost.

Diercks, *et al*. (1995) describe the, still under construction, camera which was used in 1998 through early January 2000[2], and mention that it is planned to be used on: "… *the 57-cm Perkins Schmidt telescope at Lowell Observatory … Prime focus of the f/1.91 telescope lies between the primary mirror and the Schmidt corrector.*

The original corrector, which was optimized for photographic work, will be replaced with a corrector which better matches the CCD's redder QE curve. The strong curvature of the telescope's focal plane is flattened by a plano-convex lens mounted only 1mm from the focal plane. Spot diagrams show 80 percent of the light from a point source falling in a single on-axis pixel and a maximum distortion of 0.3 at the edge of the 4° field. The final f ratio of 1.91 gives a plate scale of 189 arcsec/mm or 2.8 arcsec/pixel.

The camera will reside at the prime focus of the telescope and contains a pair of 2048x2048 pixel CCDs. We have designed the camera to be easily upgraded to 2048x4096 pixel devices and it is our intention to implement this upgrade as soon as possible. The columns of the CCDs will be aligned North-South on the sky as the system is optimized to operate in "time-delay-integration" mode (TDI). The camera can also take standard "stare" mode images."

As determined from the actual images (Figs. 1 and 2), the installed camera contained a single 2098x4146 CCD (in general agreement with Miceli, *et al*., 2008). This was the camera used to produce the LONEOS-I survey images.

Also, the new (22-inch, 56-cm) corrector plate mentioned by Diercks, *et al*. (1995) had replaced the original (16-inch, 41-cm) corrector plate sometime between 1998/04/05 and 1998/04/27 (Skiff, 2022/11/22 17:53 email). Thus, all the LONEOS-I and LONEOS-II survey images we have were obtained with the 22-inch corrector plate.

Koehn and Bowell (1999): "… *59-cm Schmidt telescope … We are currently (July 1999) searching the sky at a steady monthly rate of about 6,000 deg^2 to a typical limiting magnitude of V = 18.4 (for moving objects at a 50% detection probability). By fall 1999, we hope to have installed a new CCD camera, which will afford twice the DQE, a FOV of 9 deg^2 (80% larger than that of our present camera), and more than a 50% increase in observational duty cycle. Later, we hope to improve the corrector plate's optical performance and to improve dome seeing. Together, these enhancements should allow us to increase monthly sky coverage (three passes per region) to 20,000 deg^2 --which represents the entire accessible dark sky--and to increase the search limiting magnitude to V = 19.2 or fainter.*" This abstract was written about halfway through the LONEOS-I survey and is primarily looking forward to beginning operations with a new camera.

Koehn and Bowell (2000) write that the survey: "… *uses an automated 58-cm Schmidt telescope … Nightly observing started in March 1998 … We have recently installed a Lowell-built CCD camera. … Compared to the original camera, the new camera has a shorter read time (12 sec vs. 45 sec), a higher peak quantum efficiency (85 sq), lower read noise, and far fewer defects. Using a slightly modified observing technique (4 passes rather than 3) we are now observing about twice as much sky each hour. New software allows us to detect sources at 1.7-sigma above background. Together, the software and observing technique have increased our limiting magnitude to V=19.3 while decreasing the number of false detections.*"

This is the first report I could find describing operating with the telescope / camera used to conduct the LONEOS-II survey.

The first publication with hard information on the LONEOS-II survey is a paper in the *Asteroids III* book by Stokes, Evans, and Larson (2002). However, it has little detailed information on the camera or other details of the program. Below, in its entirety, is all it has to say about the LONEOS program:

"*The Lowell Near-Earth Object Survey (LONEOS) is run by Lowell Observatory (E. Bowell, B. Koehn) and utilizes a 0.59-m (f/1.0) modified Schmidt telescope located at the Lowell Anderson Mesa site near Flagstaff, Arizona. Two cryocooled 2048 × 4096 Marconi CCDs with 0.0135-mm, 2.4-arcsec pixels*

---

[2] In what became the LONEOS-I survey for which we have images from 1997/10/27 through 2000/01/11.

provide a total FOV of 8 deg^2. Using an unfiltered stare mode with 45-s integration, the system is capable of reaching V ~ 19.3 and can be run automatically.

The system utilizes four visits, and moving-object detection is automatic, although the observer can visually inspect candidate objects in near real time and compute short-arc Vaisala orbits to identify possible NEAs.

The LONEOS approach of using a large-format CCD with large pixels and large FOV has been successful.

Future plans include a collaboration with scientists at the U.S. Naval Observatory Flagstaff Station using a new mosaic camera on their 1.3-m telescope, which should double the current LONEOS discovery rate. Even further in the future is the potential 4-m Next Generation Lowell Telescope with a 3.2-deg^2 FOV and V ~ 22.3."

In addition to the above (probably provided by Bowell and Koehn), Stokes, *et al*. (2002)'s Table 2 (Discovery statistics for current search programs as of February 2002) gives the following for LONEOS observations through February 2002: "*Discoveries 12,713, NEAs discovered 106, 45 months of operation*". This means the first month of operation was 01 May 1998, which is in reasonable agreement with the date of the first image we have (1998/04/25).

Useful information on the system used to conduct the LONEOS-II survey are also available from Stokes, Evans, and Larson's Table 1, which is discussed in §3, below.

Post-survey publications are:

Miceli, *et al*. (2008), who reported using LONEOS data to study RR Lyrae variable stars and which provides information on the early years of the survey, *viz*.: "… *LONEOS is carried out with a 0.6 m Schmidt telescope. During the first two years of operation, imaging was done with a camera constructed at the University of Washington (Diercks et al. 1995), with a single 2Kx4K unfiltered CCD (5 deg^2 FOV with 2.67" pixel^{-1}; LONEOS-I). Under optimal conditions, LONEOS can image up to 1000 deg^2 per night, multiple times. The LONEOS-I survey imaged fields three times a night with 60 s exposure times. Fields are reobserved at least one other time about one lunation later. LONEOS-I camera uses no bandpass filter, but the data can be transformed to a standard photometric system using external data sets. The LONEOS-I camera can reach a depth of R ~ 18.5.*

…

The LONEOS-I photometric variability database discussed in this paper consists of photometric data obtained between 1998 and 2000. It covers a large fraction of the sky, much of it imaged in multiple epochs (see Fig. 1). The LONEOS-I data set that we will analyze in this paper consists of 1430 deg^2 with at least 28 epochs."

Finally, in their unpublished 2008 manuscript (Appendix I), written after completion of the LONEOS survey, (Bowell, *et al*., 2008) wrote: "*Lowell Observatory had acquired a 0.6-m f/1.8 Schmidt telescope from Ohio Wesleyan University in 1990, and by 1992 had secured funding from NASA to equip the focal plane with a 4-million pixel CCD camera, built by collaborators from the University of California, Santa Barbara, and Lawrence Livermore National Laboratory. The Schmidt telescope, built for photography, was given a very extensive facelift by mechanical designer Ralph Nye, and was equipped with modern electronics by Rich Oliver (figures 1, 2, and 3). For various reasons, progress in getting the telescope, its associated computers, and the software in working order was painfully slow---to the point that we thought funding might be cut off. We finally achieved first light in January 1998, though many of our first detected "asteroids" embarrassingly turned out to be artifacts in the CCD images. Subsequently, we equipped LONEOS with a Lowell-built 17-million pixel camera, designed by instrumentation specialist Ted Dunham, and Koehn (figure 4) greatly improved the moving-object detection software*."

3. THE "LONEOS SURVEY": TELESCOPES AND CAMERAS

The information below is from the publications in §2 and examination of the FITS images' headers.

a) Telescopes

There were two versions of the "LONEOS telescope": the telescope originally received from Ohio Wesleyan University in 1990, described as "... *a 0.6-m f/1.8 Schmidt telescope*" in Bowell, Koehn, and Skiff (2008) and the modified version that obtained all the survey images.

Not stated in any of the LONEOS-related publications I could find is the fact that the original telescope received from Ohio Wesleyan University had a 16-inch corrector plate and so is more accurately referred to as the "16-inch Schmidt telescope", as it was called when it was at the Perkins Observatory (Phillips, 1992), and traditionally described as a "16-inch (0.41-meter) aperture with a glass corrector plate and a 24-inch (0.61-meter) f/1.81 primary mirror"[3].

The "LONEOS telescope" is variously described in the publications in §2 as a 58cm, f/1.91; 57cm; 59cm; 58cm; 0.59m, f/1.0; 0.6m; and 0.6m, f/1.8 "Schmidt telescope" or "modified Schmidt telescope" (with "modified" not defined). However, with information from §2, *viz*., Diercks, *et al*. (1995) on the field flattener and Skiff's (2022/11/22 17:53 email) regarding the corrector plate, it's likely that the modification consisted of flattening the curved focal plane by adding a plano-convex lens mounted 1mm from the focal plane and replacing the 16-inch corrector plate with a 22-inch corrector plate.

b) Cameras

Other than the size of the CCD array (header keywords NAXIS1, NAXIS2) and, sometimes, information on the amplifiers used to read out the CCD, the only camera-specific information in the image headers was in the INSTRUME, DETECTOR, GAIN, RDNOISE, and PIXSCALE keywords. However, since the values of many of these keywords are demonstrably wrong, their utility is questionable.

i) The LONEOS-I Camera

The camera used in the LONEOS-I survey (*i.e*., all images we have that were obtained prior to 2000/02/04) was substantially that described in Bowell, *et al*. (1995) as: "… *a CCD camera containing two Loral 2048x2048 chips (eventually two 2048x4096 chips), a Silicon Graphics IRIS 4D/220GTX computer containing six processors, and other computers*." and Diercks *et al.,* 1995 / Miceli, *et al*. (2008): "*During the first two years of operation, imaging was done with a camera constructed at the University of Washington (Diercks et al., 1995), with a single 2Kx4K unfiltered CCD (5 deg^2 FOV with 2.67" pixel^{-1}; LONEOS-I).*". However, the header keywords for these images have NAXIS1, NAXIS2 = 2098, 4146.

As an example, two images, the first and last obtained in the LONEOS-I survey (199804250001b.fits and 200001110004b.fits in Figs. 1 and 2,), show that all pixels in column 1 (the east side) have values in the 700s (*i.e*., ~dead), all those in column 2 have values in the high 3000s and low 4000s, and all those in column 39 are saturated (*i.e*., have values 16384). Columns 3 through 38 have the same background and star images as those in columns 40 through 2049. Columns 691-797, 828, 966-971, and 1852 have values in the 700s, and columns 1263 and 2041 are saturated (values of 16382). On the west side, columns 2050 through 2098 have values in the 700s. Hence, all useful image data are in columns 3 through 2049 less those I described herein as ~dead or saturated. Row 4097 has values about twice that of 4096, and 4098 through 4146 have values in the 300s except for those with saturated columns which extend from 4097 through 4146.

All LONEOS-I images have embedded WCS information, but none have a Lowell Observatory Imaging Software (LOIS) version or any other information on the software used to readout the images and all exposures were obtained with no filter.

---

[3] The "48-inch Palomar Schmidt telescope", when it went into operation in 1948, and through 1987 when it was renamed the "48-inch Samuel Oschin Telescope", is described as being: "… *a 48-inch (1.2-meter) aperture with a glass corrector plate and a 72-inch (1.8-meter) f/2.5 mirror*." Hence, the "LONEOS Schmidt telescope" is more properly referred to as the "16 (or 22)-inch LONEOS Schmidt telescope" The f/1.81 is explained at the end of §3c. https://sites.astro.caltech.edu/palomar/about/telescopes/oschin.html

ii) The LONEOS-II Camera

A high-level description of the camera used in the LONEOS-II survey is given in Koehn and Bowell (2000): "*We have recently installed a Lowell-built CCD camera. … Compared to the original camera, the new camera has a shorter read time (12 sec vs. 45 sec), a higher peak quantum efficiency (85 sq), lower read noise, and far fewer defects.*" and in Stokes, Evans, and Larson (2002): "... *Two cryocooled 2048 × 4096 Marconi CCDs with 0.0135-mm, 2.4-arcsec pixels ...*" and in Stokes, *et al*. Table 1 (Comparison of current near-Earth object search programs) incorporated into Table 1, below.

See loneos_processing_details.pdf for the details on how the original images received on HDDs from the Lowell Observatory were converted to augmented images and loneos_augmented_images_validation.pdf for an in-depth discussion of the LONEOS-II survey's augmented images cropped to remove overscan columns and with added WCS information.

None of the original LONEOS-II images have embedded WCS information but all have a LOIS keyword indicating the software used to readout the images and all exposures were made with no filter.

c) The LONEOS System

From the information in §3a and §3b we can describe the two LONEOS Systems (telescope + camera) used to obtain the images in the LONEOS-I and LONEOS-II surveys. These are presented in tabular form in Table 1 which is adapted from Table 1 (Comparison of current near-Earth object search programs) in Stokes, Evans, and Larson (2002). The primary difference between the two tables is that the one given here replaces the first line (Aperture (m)) with two lines (Corrector Plate (m), Primary Mirror (m)), adds a Focal Length line, and removes the last line (Effective Coverage) from the Stokes, Evans, and Larson (2002) table since that term was not defined.

Table 1. Comparison of LONEOS-I and LONEOS-II Systems.

	LONEOS-I	**LONEOS-II**
Corrector Plate (m)	0.56	0.56
Primary Mirror (m)	0.61	0.61
Focal Length (mm)	1100	1100
f Number	1.81	1.81
Telescope Type	0.56m-Schmidt	0.56m-Schmidt
Array Dimensions	2098x4146	4296x2050 x 2
Pixel Size (mm)	0.0150	0.0135
Pixel Size (arcsec)	2.80	2.53
FOV (deg^2)	5.2	8.3
Cooling (°C)	-50	-130
Readout Mode	stare	stare
CCD Type	thick	thin
Exposure (sec)	60	45
Magnitude Limit	18.4V	19.3V
Coverage (deg^2/h)	200	400
Number of Visits	3	4

With the exception of the "Focal Length", "f Number" (usually called the "Focal ratio"), and "Pixel size", the values in this table are taken, or can be derived from, the material presented in §§2 and 3, above.

Blind astrometric solutions to the LONEOS-I and LONEOS-II images using Astrometry.net give plate scales, *i.e.*, the "Pixel Size (arcsec)" of the images, as 2.80 and 2.53 arcsec/pixel, respectively. Since identical telescopes were used to obtain the images, the difference in the numerical values (2.80 vs. 2.53) is due to the different pixel sizes of the camera's CCDs. The LONEOS-I images were obtained with a 15-µm pixel^{-1} CCD and the LONEOS-II images with a 13.5-µm pixel^{-1} CCD. Then, from the "Pixel Size", in arcsec/pixel and in pixel/mm, the plate scale for each survey, in "/mm, can be obtained by dividing the pixel size in arcsec/pixel by the pixel size in mm resulting in plate scales of 186.7 and 187.4 "/mm for the LONEOS-I and LONEOS-II images, respectively. These differ by 0.7 "/mm (0.40%) and their mean is 187.0 ± 0.4 "/mm from which one can derive the focal length to be 1103 ± 2 mm. Then, given that the diameter of the primary mirror is 24-inches (a standard mirror blank size in the United States at the time and which included 6, 8, 10, 12, 16, 24, and 32-inches) or 610 mm, the focal ratio is 1.808 ± 0.003. Hence, the LONEOS telescope is a “22-inch (0.56-meter) aperture with a glass corrector plate and a 24-inch (0.61-meter) f/1.81 primary mirror”**[4]**. This is in good agreement with the Bowell, *et al*. (2008) description of the telescope received from Ohio Wesleyan University in 1990, which they describe as being: "... *a 0.6-m f/1.8 Schmidt telescope*”. Note that replacing the original 16-inch corrector plate with a 22-inch corrector should have no effect on the focal length since in a Schmidt telescope the focal length is determined solely by the primary mirror’s diameter and focal ratio.

4. THE “LONEOS SURVEY”: OBSERVING STRATEGY

From Koehn and Bowell (2000):

Prior to 2000/02/04 (LONEOS-I): A goal of three 60s exposures of each area imaged.

After 2000/02/04 (LONEOS-II): A goal of four 45s exposures of each area imaged.

However, some images were obtained with exposure times other than those above.

The nightly sky regions chosen to observe were loosely coordinated with those of other programs. See Stokes, Evans, and Larson (2002), §5 (Coordination of Search Programs), for a discussion of this.

5. THE “LONEOS SURVEY”: IMAGES

From the information obtained from the publications in §2 and examination of the images’ headers I infer the following.

The data**[5]** we received from the Lowell Observatory, some on hard disk drives (HDD) and others *via* recovery from tapes received via the Jet Propulsion Laboratory (JPL), contained images obtained between 1997/10/27 and 2011/06/16 (see loneos_data_acquisition.pdf). Initially, we assumed the images on these HDDs and tapes constituted the “LONEOS Survey” but that turned out not to be the case.

Examination of a substantial subset of all the images we received from the Lowell Observatory led me to conclude that all images obtained prior to 2000/02/04 were not part of the LONEOS Survey as described in Stokes, Evans, and Larson (2002) because these images were not obtained with the LONEOS telescope and camera/detector described therein. While this turned out to be true, it was not the whole story, as discussed in §§2, 3, and 4, above. In any case, the original LONEOS Dataset**[6]** (*i.e*., all the data received on HDDs and tapes) consists of data from the three distinct phases described in Table 2.

Phase 0) includes those images obtained between 1997/10/27 and 1998/04/04 using the LONEOS-I camera and the 16-inch, “perhaps slightly masked” (Skiff, 2023/12/12 14:16 email), Schmidt telescope.

Phase 1) consists of all images obtained between 1998/04/25 and 2000/01/11. All of these were obtained using the LONEOS-I camera and 22-inch Schmidt telescope. These images were used in a study regarding components of the Galactic stellar halo by Miceli, *et al*. (2008) who referred to this collection of images as the “LONEOS-I Survey”.

Phase 2) comprises the LONEOS-II Survey Images, *i.e.*, all images obtained between 2000/02/04 and 2008/03/01. These images were obtained using the LONEOS-II camera and 22-inch Schmidt telescope.

Phase 3) includes all images obtained after between 2010/01/04 and 2011/06/16. These are post-survey images, obtained as part of the follow-on Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS) program (Koehn, *et al*., 2014; Skiff, *et al*., 2012, 2019a, 2019b). This program obtained lightcurves for a sample of NEAs. We have images from this phase from 2010/01/04 through 2011/06/16, all of which were obtained with the LONEOS telescope and LONEOS-II camera (although only a portion

---

[4] Another way to describe a Schmidt telescope is 56/61/110 cm where 56 is the corrector plate aperture, 61 the mirror diameter and 110 the focal length, with all values in centimeters. Values here are for the LONEOS Schmidt.

[5] The original images obtained on hard disk drives are in archive …\data_original\.

[6] https://sbnarchive.psi.edu/loneos/

of the CCD was still useable during this period). The NEAPS images obtained with telescopes other than the LONEOS telescope are not among the images we received from the Lowell Observatory.

Table 2. Source of FITS Images by Year and Month

Year	Month(s)	Source[a]	Phase[b]
1997	10-12	Tape	0
1998	(04), 04-12	Tape	(0), 1
1999	01,02,05,06,08,09	Tape	1
2000	(01), 02-06, 09-12	HDD (03) and Tape	(1), 2
2001	01-11	Tape	2
2002	06,07,12	Tape	2
2003	01-12	HDD (04-12), Tape (01-05)	2
2004	01-12	HDD	2
2005	11-12	HDD	2
2006	01-10, 12	HDD	2
2007	01-12	HDD	2
2008	01-03	HDD	2
2010	01,03-10	HDD	3
2011	02-06	HDD	3

[a] The numbers in parentheses are the source for images obtained for those months. If there are no numbers in parentheses then all months were obtained from that source.

[b] The numbers in parentheses mean the months in parentheses were obtained in that phase.

Note that the 45 months of operation for the "LONEOS Survey" through 2002/02/28, given in Stokes, Evans, and Larson (2002), means the first month of operation was May 1998. This is reasonably consistent with the first image we have from the LONEOS-I Survey (1998/04/25 which is exactly 46 months prior to 2002/02/28[7]). However, the images obtained between 1998/04/25 and 2000/01/11 were not obtained with the LONEOS telescope and camera/detector described in Stokes, Evans, and Larson (2002), as can be seen in Figs. 1 and 2, (the first and last of the LONEOS-I images). Hence, the statement that, as of 2002/02/28, the "LONEOS Survey" had been in operation for 45 months is misleading because Stokes, Evans, and Larson (2002) defined the "LONEOS System as utilizing: "… a *0.59-m (f/1.0)*[8] *modified Schmidt telescope located at the Lowell Anderson Mesa site near Flagstaff, Arizona. Two cryocooled 2048 × 4096 Marconi CCDs with 0.0135-mm, 2.4-arcsec pixels provide a total FOV of 8 deg*^{2}. *Using an unfiltered stare mode with 45-s integration*, …".

```
SIMPLE  =                    T /
BITPIX  =                   16 /
NAXIS   =                    2 /
NAXIS1  =                 2098 /
NAXIS2  =                 4146 /
BSCALE  =             1.000000 /
BZERO   =         32768.000000 /
EXTEND  =                    F /
UNSIGN  =                    F /
```

---

[7] Based on the images we received from the Lowell Observatory, various pre-survey images were obtained starting as early as 1997/10/27 (tape image f0000008.fits at 01:00:16.00 UT – a "sky flat" and f1560747.fits at 05:39:35.00 UT – a 1 second exposure of Vega COMMENT = 'Alignment run', the AN-determined plate scale for which is 2.82 "/pixel).

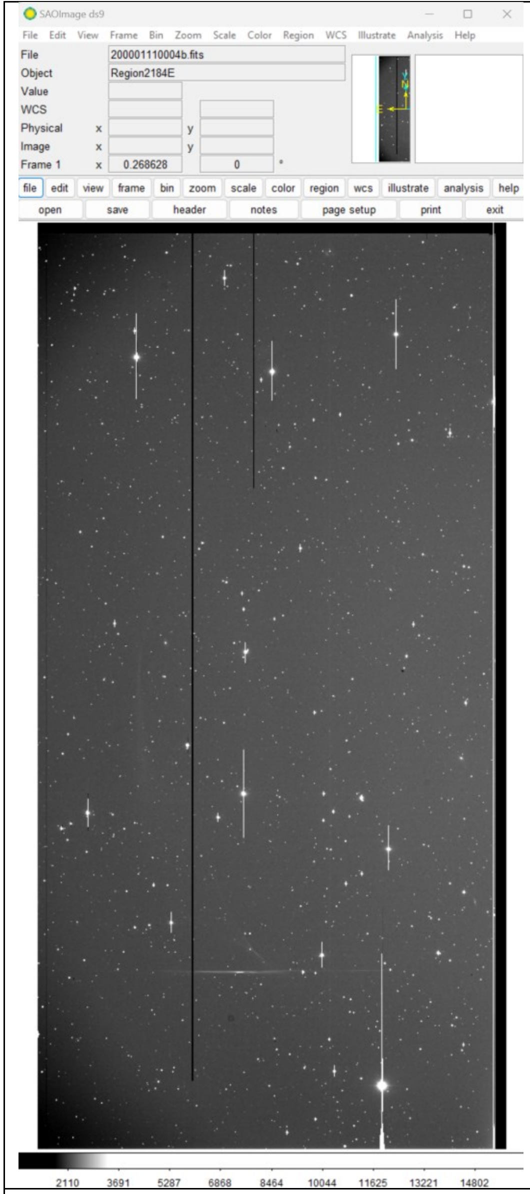
[8] f/1.0 may be a typographical error since a 0.59m f/1.0 telescope would have a plate scale of 4.72 "/pixel. This same paper's Table 1 gives specs for the LONEOS system, *as:* "*Aperture 0.6m, f/1.9, 2048x4096x2, 0.0135mm/px, 2.5"/px* …" for which the computed plate scale is 2.44"/pixel. In reality, the plate scale determined by numerous Astrometry.net solutions to images obtained with this system is 2.53"/pixel so the aperture and/or f/ratio are incorrect but by a small amount, *e.g.*, a 0.58m, f/1.9 system would have a plate scale of 2.53"/pixel.

File 199804250001b.fits
Object Region1893
Frame 1 x 0.268628 0 °

```
TELESCOP= 'APO 3.5m '          / Telescope used for
observation
ORIGIN  = 'Apache Point Observ / Observatory Location
LATITUDE=            32.780361 / Observatory Latitute
(degrees)
LONGITUD=           105.820417 / Observatory longitude
(degrees)
INSTRUME= 'Spicam          '   / Instrument used for
observation
DETECTOR= 'Spicam CCD      '   / Detector used for
observation
GAIN    =             1.000000 / Nominal Gain (e/DN)
RDNOISE =             5.000000 / Nominal Read Noise (DN)
PIXSCALE=            0.140000  / Nominal unbinned Pixel
Scale (arcsec)
IMAGETYP= 'LIGHT             ' / exposure mode
CCDPICNO=                    1 / running sequence number
OBJECT  = 'Region1893        ' / object name
DATE-OBS= '98/04/25          ' / local date of obs
DATE-UT = '98/04/25          ' / ut date of obs
DATE-RD = '98/04/24          ' / local date of CCD read
EXPTIME =            60.000000 / actual exposure time
DARKTIME=             3.060895 / total darktime
REQTIME =            60.000000 / requested exposure time
OPENTIME=            60.091583 / approx measured exposure
time
SHORTEXP=                    F / true: fast shutter, false:
slow shutter
FILTER  = 'a                 ' / filter name
FILTNUM =                    1 / filter wheel slot number
JD      =             0.000000 / Julian Day when shutter
opened
UT      = '04:38:44.00       ' / UT when shutter opened
ST      = '11:24:35.00       ' / Siderial Time when shutter
opened
COORDSYS= 'FK5               ' / coordinate system
EQUINOX =          2000.000000 / system equinox
ROTATE  =             0.000000 / image rotation (decimal
degrees)
FOCUS   =         -9900.000000 / TCC reported focus
CCDTEMP =           -99.000000 / reported temperature
CCDBIN1 =                    1 / binning in X direction
CCDBIN2 =                    1 / binning in Y direction
COMMENT = 'Region 1893 west, Pass 1 ' /
RA      = '13:09:02.00       ' / RA at CCD Center (hours)
DEC     = '-06:18:37.00      ' / DEC at CCD Center (degrees)
HA      = '-01:44:27.00      ' / Hour Angle
ZD      = '00:48:29.25       ' / Zenith Distance
AIRMASS =             1.447482 / Airmass
CTYPE1  = 'RA---TAN          ' /
CUNIT1  = 'DEGREE            ' /
CTYPE2  = 'DEC--TAN          ' /
CUNIT2  = 'DEGREE            ' /
CRVAL1  =           197.258333 /
CRVAL2  =            -6.310278 /
CRPIX1  =          1258.400024 /
CRPIX2  =          2139.800049 /
CDELT2  =             0.000000 /
CDELT1  =            -0.000000 /
PC001001=             1.000000 /
PC001002=            -0.000000 /
PC002001=             0.000000 /
PC002002=             1.000000 /
NCCD    =                    1 / CCD number
END
```

Fig. 1. A typical image from the first night (1998/04/25) of the LONEOS-I survey (left) and its header (right).

```
SIMPLE  =                    T /
BITPIX  =                   16 /
NAXIS   =                    2 /
NAXIS1  =                 2098 /
NAXIS2  =                 4146 /
BSCALE  =             1.000000 /
BZERO   =         32768.000000 /
EXTEND  =                    F /
UNSIGN  =                    F /
TELESCOP= 'Loneos 30cm      ' / Telescope used for observation
ORIGIN  = 'Lowell Observatory' / Observatory Location
LATITUDE=            35.095930 / Observatory Latitute (degrees)
LONGITUD=           248.463310 / Observatory longitude (degrees)
```



File 200001110004b.fits
Object Region2184E
Frame 1 x 0.268628 0 °

```
INSTRUME= 'Astrocam           ' / Instrument used for observation
DETECTOR= 'Thick CCDs         ' / Detector used for observation
GAIN     =             5.000000 / Nominal Gain (e/DN)
RDNOISE  =            10.000000 / Nominal Read Noise (DN)
PIXSCALE=              2.670000 / Nominal unbinned Pixel Scale
(arcsec)
IMAGETYP= 'light              ' / exposure mode
CCDPICNO=                     4 / running sequence number
OBJECT   = 'Region2184E       ' / object name
DATE-OBS= '00/01/10           ' / local date of obs
DATE-UT  = '00/01/11          ' / ut date of obs
DATE-RD  = '00/01/10          ' / local date of CCD read
EXPTIME  =            60.000000 / actual exposure time
DARKTIME=            175.516176 / total darktime
REQTIME  =            60.000000 / requested exposure time
OPENTIME=             60.223558 / approx measured exposure time
SHORTEXP=                     F / true: fast shutter, false:
slow shutter
FILTER   = 'open              ' / filter name
FILTNUM  =                    1 / filter wheel slot number
JD       =             0.000000 / Julian Day when shutter opened
UT       = '01:46:14.00       ' / UT when shutter opened
ST        = '01:39:41.00       ' / Siderial Time when shutter
opened
COORDSYS= 'FK5                ' / coordinate system
EQUINOX  =          2000.000000 / system equinox
ROTATE    =                0.000000 / image rotation (decimal
degrees)
FOCUS    =         -9900.000000 / TCC reported focus
CCDTEMP  =             0.000000 / reported temperature
CCDBIN1  =                    1 / binning in X direction
CCDBIN2  =                    1 / binning in Y direction
RA       = '02:46:37.00       ' / RA at CCD Center (hours)
DEC      = '03:09:28.00       ' / DEC at CCD Center (degrees)
HA       = '-01:06:56.00      ' / Hour Angle
ZD       = '00:37:11.09       ' / Zenith Distance
AIRMASS  =             1.228462 / Airmass
CTYPE1   = 'RA---TAN          ' /
CUNIT1   = 'DEGREE            ' /
CTYPE2   = 'DEC--TAN          ' /
CUNIT2   = 'DEGREE            ' /
CRVAL1   =            41.654167 /
CRVAL2   =             3.157778 /
CRPIX1   =          1258.400024 /
CRPIX2   =          2139.800049 /
CDELT2   =             0.003733 /
CDELT1   =            -0.003733 /
PC001001=              1.000000 /
PC001002=             -0.000000 /
PC002001=              0.000000 /
PC002002=              1.000000 /
NCCD     =                    1 / CCD number
COMMENT  = 'Region 2184 east, ' /
END
```

Fig. 2. A typical image from the last night (2000/01/11) of the LONEOS-I survey (left) and its header (right).

The headers for these images indicate, for 1998/04/25 (Fig. 1):

```
TELESCOP= 'APO 3.5m           ' / Telescope used for observation
ORIGIN   = 'Apache Point Observ / Observatory Location
LATITUDE=             32.780361 / Observatory Latitute (degrees)
LONGITUD=            105.820417 / Observatory longitude (degrees
INSTRUME= 'Spicam             ' / Instrument used for observation
DETECTOR= 'Spicam CCD         ' / Detector used for observation
GAIN     =             1.000000 / Nominal Gain (e/DN)
RDNOISE  =             5.000000 / Nominal Read Noise (DN)
PIXSCALE=              0.140000 / Nominal unbinned Pixel Scale (arcsec)
```

And for 2000/01/11 (Fig. 2):

```
TELESCOP= 'Loneos 30cm        ' / Telescope used for observation
ORIGIN   = 'Lowell Observatory' / Observatory Location
LATITUDE=             35.095930 / Observatory Latitute (degrees)
LONGITUD=            248.463310 / Observatory longitude (degrees)
INSTRUME= 'Astrocam           ' / Instrument used for observation
DETECTOR= 'Thick CCDs         ' / Detector used for observation
GAIN     =             5.000000 / Nominal Gain (e/DN)
RDNOISE  =            10.000000 / Nominal Read Noise (DN)
PIXSCALE=              2.670000 / Nominal unbinned Pixel Scale (arcsec)
```

Table 3. Astrometry.net solutions for the images in Figs 1 (left) and 2 (right).

```
Submitted by anonymous (1) on 2023-12-9T01:53:24Z
as “ 199804250001b.fits “ (Submission 8879146)
under Attribution 3.0 Unported
Job Status
Job 9605600: Success
Calibration
Center (RA, Dec): (195.209, -6.319)
Center (RA, hms): 13h 00m 50.063s
Center (Dec, dms):   -06° 19’ 07.062”
Size: 1.63 x 3.22 deg
Radius:  1.807 deg
Pixel scale:   2.8 arcsec/pixel
Orientation:   Up is -179.8 degrees E of N
```

```
Submitted by anonymous (1) on 2023-12-09T01:56:41Z
as “ 200001110004b.fits “ (Submission 8879154)
under Attribution 3.0 Unported
Job Status
Job 9605608: Success
Calibration
Center (RA, Dec): (43.881, 3.112)
Center (RA, hms): 02h 55m 31.546s
Center (Dec, dms):   +03° 06’ 41.499”
Size: 1.63 x 3.22 deg
Radius:  1.807 deg
Pixel scale:   2.8 arcsec/pixel
Orientation:   Up is -179.9 degrees E of N
```

In spite of what is contained in the header of 199804250001b.fits, we have no images obtained with the Apache Point Observatory (APO) 3.5m telescope because: “*The ARC 3.5-meter telescope is designed with an altitude-azimuth mount. The primary and secondary mirrors provide a working f/number of 10.4 and an effective focal length of 35238.7 mm*.” (Gillespie, Loewenstein, and York, 1996). And: “*The Apache Point Observatory (APO) is home to the Astrophysical Research Consortium (ARC) 3.5m f/10 alt-az telescope …*” (Chanover and Williams, 2020). So, this telescope’s characteristics have remained unchanged during the entire duration of the LONEOS / NEAPS programs.

The APO telescope’s 35238.7 mm focal length means its plate scale is 0.088 “/mm which, with a 2098x4146 CCD with 15μm pixels, works out to a FOV of 3.07’x6.07’, not the 2.88°x2.88° that all complete (*i.e.*, _1 + _2) LONEOS images have. What we do have are images which mention the APO in their headers, but those images’ plate scales are 2.8 “/mm and so were clearly NOT obtained with the APO.

However, as shown in the Astrometry.net (AN) solutions to the pre-2000/02/04 images in Table 3, the plate scale of these images is 2.8”/pixel and the image size is 1.63° x 3.22° whereas those for the instrument described in Stokes, Evans, and Larson (2002) Table 1 are 2.53”/pixel and the image size is 2.88° x 1.44° which applies to the Phase 2 images, *e.g.*, to those shown in Fig. 3 and Table 4.

Hence, it appears likely that the LONEOS-I images purported to have been obtained with the 'APO 3.5m' were actually obtained with the 'loneos 30cm' telescope, although this begs the question of what the specifications were for the 'loneos 30cm' telescope. According to Brian Skiff (2022/11/22 17:53 email): *“… the first e-mailed astrometry file with the LONEOS MPC observatory code 699 was sent 1998 Mar 6; me and Bruce Koehn evidently observing, and the telescope is called “0.37-m LONEOS Schmidt + CCD”*.” Note: 0.37-m is 14.6-inch so this is likely the original, “perhaps slightly masked” 16-inch, Schmidt telescope (Skiff, 2023/12/12 14:16 email.)

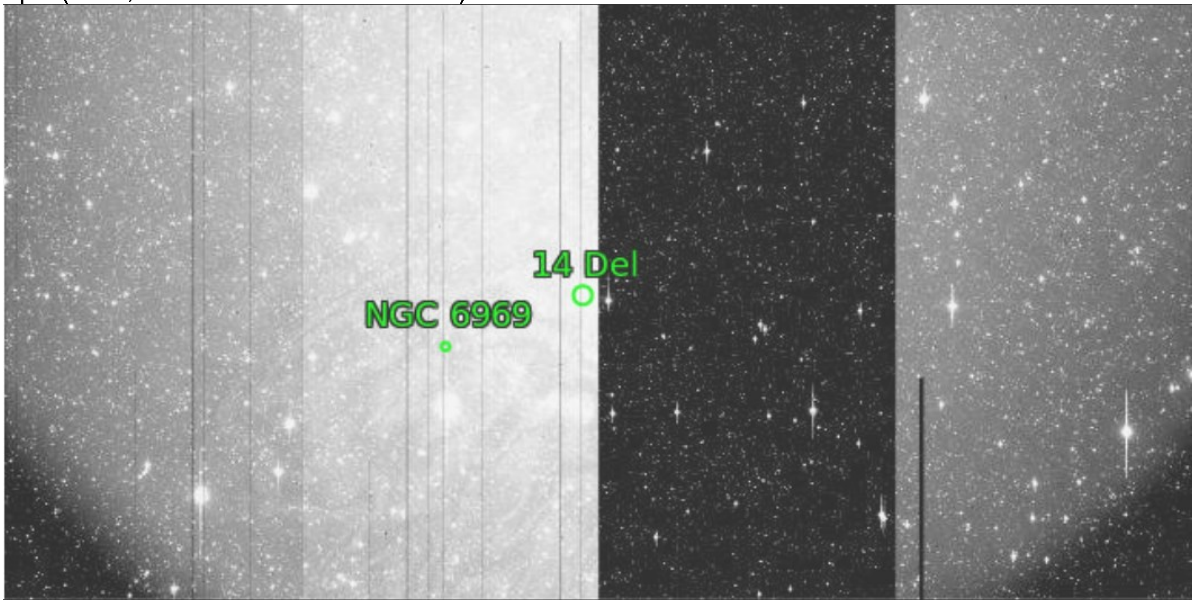


Fig. 3. Astrometry.net fit to LONEOS-II Survey image 051113_2_014.fits.

Table 4. Astrometry.net solutions for 051113_2_014.fits.

```
Center (RA, Dec):   (312.489, 7.847)
Center (RA, hms):   20h 49m 57.382s
Center (Dec, dms): +07° 50' 49.247"
Size:               2.88 x 1.44 deg
Radius:             1.609 deg
Pixel scale:        2.53 arcsec/pixel
Orientation:        Up is -179.8 degrees E of N
```

Based on the images we have; the durations[9] of the various phases are:

Phase 0 (the pre-survey) – 1997/10/27 through 1998/04/04: 5 months, 9 days (160 days)

Phase 1 (the LONEOS-I survey) – 1998/04/25 through 2000/01/11: 20 months, 18 days (627 days)

Phase 2 (the LONEOS-II survey) – 2000/02/04 through 2008/03/01: 96 months, 27 days (2,949 days)

Phase 3 (the NEAPS program) – 2010/01/04 through 2011/06/16: 17 months, 13 days (529 days)

Images obtained in Phases 0 and 1, using the LONEOS-I camera, have no LOIS information.

All images from Phases 2 and 3 were obtained with the LONEOS-II camera using six different versions of readout software identified using the header keyword LOISVERS with the versions shown in Table 5. Those from Phase 2 used versions 1.1 to 4.2, and those from Phase 3 used version 4.2.

Table 5. LOIS Versions[a]

LOISVER	Date Range	LOISVER	Date Range
None	1997/10/27 to 2000/01/11 T	2.0.0.beta	2002/12/09 to 2003/07/09 T, HDD
1.1	2000/02/04 to 2002/03/02 T	3.2.0.beta	2003/08/05 to 2004/12/26 HDD
1.3.2.2beta	2002/06/08 to 2002/06/20 T	4.2	2005/11/13 to 2011/06/16 HDD
1.3.3.0	2002/07/06 T		

[a] T = Obtained from Tapes, HDD = Obtained from Hard Disk Drives.

6. REFERENCES

The references below, except for the NEAPS publications, include the entire text for Abstracts and the relevant portions of published papers. The unpublished manuscript (Bowell, *et al.*, 2008) is included as Appendix I.

Bowell, E., Koehn, B.W., Howell, S.B., Hoffman, M., and Muinonen, K. (1995). The Lowell Observatory Near-Earth-Object Search: A Progress Report. American Astronomical Society, DPS Meeting #27, id.01.10; *Bulletin of the American Astronomical Society*, **27**, p.1057 1995BAAS...27.1053)

Abstract

The Lowell Observatory Near-Earth-Object Search (LONEOS) is a system to survey asteroids and comets that has been under development for a little more than 2 years. Hardware consists of a 58-cm f/1.91 Schmidt telescope, a CCD camera containing two Loral 2048x2048 chips (eventually two 2048x4096 chips), a Silicon Graphics IRIS 4D/220GTX computer containing six processors, and other computers. The instantaneous field of view will be 10.1 deg^2. To image the sky, the telescope will scan in declination at a rate up to 6 deg/min. corresponding to a data-acquisition rate of 1 Mb/s. The system will have the capability of scanning the entire accessible dark sky three times per lunation to a limiting magnitude that should exceed V_{ta}= 19 J. Scans will he made on fixed regions of the sky, so images of fixed celestial sources (stars, galaxies, *etc.*) and repealing cosmetic defects (diffraction spikes, bleeding from saturated stars, *etc.*) will always occupy known pixels. By co-adding a number of scans, we will build fixed-source maps, which will allow moving-target detection only in pixels thought to contain dark sky.

---

[9] These durations are the periods, inclusive, between the first and last images we received. There are likely images before or after these dates, or within the range of dates, that were obtained but that we did not receive.

Initially, such detections will be made only on the basis of data numbers exceeding a chosen threshold. During the past few months we have been developing algorithms to maximize V_{lim} (*i.e.*, minimize the S/N ratio and the false-positive detection rate). Because LONEOS is close to undersampling (untrailed images will occupy no more than 16 pixels), the detection process must be carried out with care. First, by examining unsaturated star images (~ 10sec/scan), wc determine the point-spread function (PSF, itself a function of zenith angle and off-axis distance in R.A.) to subpixel resolution. Then, by allowing the peak of the PSF to occupy each subpixel of the pixel containing the peak signal, we develop a family of "PSF masks." Finally, putative moving-target detections are tested against the masks, and are accepted or rejected on the basis of X^2 tests. The best-fit mask provides position and brightness estimates.

****

Bowell, Koehn, and Skiff (2008) Unpublished (as far as we know) Manuscript[10]

See Appendix I.

****

Chanover, N.J. and Williams, B. 2020 American Astronomical Society meeting #235, id. 175.24. *Bulletin of the American Astronomical Society*, **52**, No. 1. https://assets.pubpub.org/rynkboj6/71582749259388.pdf#abs175.24

****

Diercks, A.H., Angione, J., Stubbs, C.W., Cook, K.H. and 4 others. 1995. 8-megapixel thermoelectrically cooled CCD imaging system. *Proc. SPIE*, **2416**, p. 58-64, Cameras and Systems for Electronic Photography and Scientific Imaging, Constantine N. Anagnostopoulos; Michael P. Lesser; Eds. https://doi.org/10.1117/12.204839

Abstract reads:

We are developing an astronomical imaging system which employs a thermoelectrically cooled focal plane consisting of two 'edge-buttable' Loral 2048x2048 pixel CCDs. To allow strip scanning, the columns of the CCDs are mutually aligned on a custom Kovar mount. The clocking and bias voltage levels for each CCD are independently adjustable, but both CCDs are operated synchronously. Each chip is read out from one output and measured at 14 bits with commercially available A/D converters at a rate of 250 kpixels/s, permitting scanning across the sky at up to 1000 deg^2/hr (about twenty times faster than the equatorial sidereal rate) to a limiting magnitude (S/N equals 3) near V equals 19. The instrument will be used as part of the Lowell Observatory Near-Earth-Object Search (LONEOS) using a 57-cm Schmidt telescope at Lowell Observatory in Flagstaff, Arizona.

****

Gillespie, B., H.F. Loewenstein, and D. York, New observing modes for the next century, *Astronomical Society of the Pacific Conference Series*, **87**, p. 97, 1996. https://pds.nasa.gov/ds-view/pds/viewHostProfile.jsp?INSTRUMENT_HOST_ID=APO35M

****

Koehn, B.W. and Bowell, E. 1999. Enhancing the Lowell Observatory Near-Earth-Object Search. *American Astronomical Society, DPS meeting #31*, id.12.02 1999DPS....31.1202K

Abstract reads:

The Lowell Observatory Near-Earth-Object Search (LONEOS) uses a fully automated 59-cm Schmidt telescope to discover asteroids and comets that can approach the Earth. Secondary and tertiary scientific goals are, respectively, to discover other solar system bodies (main-belt asteroids, unusual asteroids, the largest TNOs), and, with extramural collaborators, to pursue a suite of non-solar system programs. Nightly observing started in March 1998, and to date we have discovered 13 near-Earth asteroids (2 Atens, 7 Apollos, and 4 Amors), and 4 comets (1 periodic). One of the Atens (1999 HF_1) is likely to be

---

[10] The manuscript lists eight figures, but the paper copy we received (below), which is from a scan, has only six.

the largest known, and 8 of the Earth approachers are probably larger than 1 km in diameter. Comet Skiff (= C/1999 J_2) has the largest known cometary perihelion distance (7.5 AU). We have submitted about 200,000 observations of asteroids to the Minor Planet Center, of which 100,000 pertain to known objects or to unknown objects that have been designated. Thus we have quickly become the fifth largest generator of asteroid astrometric data over the last decade. In terms of the discovery of larger NEOs, our search effort has, in the past year, been second only to that of LINEAR. We are currently (July 1999) searching the sky at a steady monthly rate of about 6,000 deg^2 to a typical limiting magnitude of V = 18.4 (for moving objects at a 50% detection probability). By fall 1999, we hope to have installed a new CCD camera, which will afford twice the DQE, a FOV of 9 deg^2 (80% larger than that of our present camera), and more than a 50% increase in observational duty cycle. Later, we hope to improve the corrector plate's optical performance and to improve dome seeing. Together, these enhancements should allow us to increase monthly sky coverage (three passes per region) to 20,000 deg^2 --which represents the entire accessible dark sky--and to increase the search limiting magnitude to V = 19.2 or fainter. During the coming years, we expect to discover many hundreds of NEOs.

****

Koehn, B.W. and Bowell, E. 2000. Lowell Observatory Near-Earth-Object Search Enhancements. *American Astronomical Society, DPS meeting #32*, id.14.03 2000DPS....32.1403K

Abstract reads:

The Lowell Observatory Near-Earth-Object Search (LONEOS) uses an automated 58-cm Schmidt telescope to discover asteroids and comets that can approach the Earth. Nightly observing started in March 1998, and, to date, we have discovered 41 near-Earth asteroids and 9 comets. We have submitted about 460,000 observations of asteroids to the Minor Planet Center, about half of which pertain to known objects. We have recently installed a Lowell-built CCD camera. Compared to the original camera, the new camera has a shorter read time (12 sec vs. 45 sec), a higher peak quantum efficiency (85 sq), lower read noise, and far fewer defects. Using a slightly modified observing technique (4 passes rather than 3) we are now observing about twice as much sky each hour. New software allows us to detect sources at 1.7-sigma above background. Together, the software and observing technique have increased our limiting magnitude to V=19.3 while decreasing the number of false detections. Our performance has increased a factor of seven with monthly (May/June) asteroid positions increasing from 8,400 to 58,800 and monthly NEO discoveries increasing from 1 to 8. We hope to increase our performance even more by improving the system's duty cycle, dome seeing, and telescope optics.

****

Koehn, B. W., Bowell, E.G., Skiff, B.A., Sanborn, J.J., and two colleagues, 2014. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS) - 2009 January through 2009 June. *The Minor Planet Bulletin* (ISSN 1052-8091). Bulletin of the Minor Planets Section of the Association of Lunar and Planetary Observers, **41**, No. 4, pp. 286-300. Bibcode: 2014MPBu...41..286K
https://articles.adsabs.harvard.edu/full/2014MPBu...41..286K

****

Miceli, A., Rest, A., Stubbs, C.W., Hawley, S.L., and five colleagues, 2008. Evidence for Distinct Components of the Galactic Stellar Halo from 838 RR Lyrae Stars Discovered in the LONEOS-I Survey. *Ap.J.* **678**:865-887. DOI 10.1086/533484

Abstract

We present 838 *ab*-type RR Lyrae stars from the Lowell Observatory Near Earth Objects Survey Phase I (LONEOS-I). These objects cover 1430 deg^2 and span distances ranging from 3 to 30 kpc from the Galactic center. Object selection is based on phased, photometric data with 28-50 epochs. We use this large sample to explore the bulk properties of the stellar halo, including the spatial distribution. The period-amplitude distribution of this sample shows that the majority of these RR Lyrae stars resemble Oosterhoff type I, but there is a significant fraction (26%) which have longer periods and appear to be Oosterhoff type II. We find that the radial distributions of these two populations have significantly different profiles

($\rho_{OoI} \sim R^{-2.26 \pm 0.07}$ and $\rho_{OoII} \sim R^{-2.88 \pm 0.11}$). This suggests that the stellar halo was formed by at least two distinct accretion processes and supports dual-halo models.

And, from §2 **LONEOS-I VARIABILITY SURVEY:**

The Lowell Observatory Near Earth Object Survey (LONEOS; Bowell et al. 1995) has as its primary goal the detection of potentially hazardous asteroids. Situated on the Anderson Mesa outside Flagstaff, Arizona, LONEOS is carried out with a 0.6 m Schmidt telescope. During the first two years of operation, imaging was done with a camera constructed at the University of Washington (Diercks et al. 1995), with a single 2Kx4K unfiltered CCD (5 deg^2 FOV with 2.67” $pixel^{-1}$; LONEOS-I). Under optimal conditions, LONEOS can image up to 1000 deg^2 per night, multiple times. The LONEOS-I survey imaged fields three times a night with 60 s exposure times. Fields are reobserved at least one other time about one lunation later. LONEOS-I camera uses no bandpass filter, but the data can be transformed to a standard photometric system using external data sets. The LONEOS-I camera can reach a depth of R ~ 18:5.

Besides searching for moving objects, this data set can be used to search for temporal variability, specifically of stellar objects. Data from LONEOS have been used to construct a stellar temporal variability database, from which we extracted candidate RR Lyrae stars. The cadence of LONEOS observations makes them well suited to detect short-term variability (e.g., RR Lyrae stars, binaries, and CVs), and long-term variability (e.g., QSOs).

The LONEOS-I photometric variability database discussed in this paper consists of photometric data obtained between 1998 and 2000. It covers a large fraction of the sky, much of it imaged in multiple epochs (see Fig. 1). The LONEOS-I data set that we will analyze in this paper consists of 1430 deg^2 with at least 28 epochs.

And, from §6 **CONCLUSIONS:**

In 2000, the LONEOS camera (LONEOS-II) was upgraded, and now consists of two 2Kx4K backside-illuminated CCDs, giving it an 8.1 deg^2 FOV (2.8” $pixel^{-1}$), and reaches to a depth of R ~ 19.3. Approximately one quarter of the sky is covered with more than 40 epochs of measurements. Photometric reduction and analysis of the new camera data has commenced, and results will be discussed in future papers. The LONEOS-II data should also increase our RR Lyrae sample by an order of magnitude with a wider and deeper survey area. The data from the LONEOS-II camera will produce cleaner period-amplitude distributions. This will enable us to search for additional “fine structure” in the period-amplitude distribution.

[Note: Searches for a paper or abstract with the work described in §6 were unsuccessful as were attempts to contact the authors.]

****

National Research Council. 1998. *Exploration of Near Earth Objects*. Washington, DC: The National Academies Press. https://doi.org/10.17226/6106

****

National Research Council. 2009. *Near-Earth Object Surveys and Hazard Mitigation Strategies: Interim Report*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12738

****

Phillips, E.W. (1992). A Short History of Perkins Observatory. *EJASA*, the Electronic Journal of the *Astronomical Society of the Atlantic*, **3**, Number 7. http://www.setileague.org/articles/perkins.htm

“… *16 inch and 8 inch Schmidt telescopes…. The larger Schmidt is in use at Flagstaff*.”

****

Skiff, B.A., Bowell, E., Koehn, B.W., Sanborn, J.J, and two colleagues, 2012. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS) - 2008 May through 2008 December. *The Minor Planet Bulletin*, **39**, No. 3, p. 111-130. Bibcode: 2012MPBu...39..111S
https://articles.adsabs.harvard.edu/full/2012MPBu...39..111S

****

Skiff, B.A., McLelland, K.P., Sanborn, J.J., Pravec, P., and one colleagues, 2019a. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS): Paper 3. *The Minor Planet Bulletin*, **46**, No. 3, pp. 238-265. Bibcode: 2019MPBu...46..238S https://articles.adsabs.harvard.edu/full/2019MPBu...46..238S

****

Skiff, B.A., McLelland, K.P., Sanborn, J.J., Pravec, P., and one colleagues, 2019b. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS): Paper 4. *The Minor Planet Bulletin*, **46**, No. 4, pp. 458-503. Bibcode: 2019MPBu...46..458S https://articles.adsabs.harvard.edu/full/2019MPBu...46..458S

****

Stokes, G.H., Evans, J.B., and Larson, S.M. (2002). *Near-Earth Asteroid Search Programs*, Asteroids III, W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel (eds), University of Arizona Press, Tucson, p.45-54. 2002aste.book...45S

Abstract

“The discovery of the potentially hazardous near-Earth asteroid (NEA) component of the minor-planet population has been enhanced by better detecting and computing technology. A government mandate to quantify the terrestrial impact hazard and to detect 90% of all NEAs larger than 1 km can be realistically addressed. The characteristics, capabilities, and strategies of the major search programs illustrate the challenges and solutions toward meeting the Spaceguard goal. This chapter reviews the historical context of early asteroid detection and of the current and anticipated search programs. It describes the search systems and discusses challenges in maximizing the NEA detection rate.”

This paper discusses Spacewatch, NEAT, LONEOS, LINEAR, CSS, and Bisci. Table 1 gives specs for the LONEOS system, viz., Aperture 0.6m, f/1.9, 2048x4096x2, 0.0135mm/px, 2.5”/px, FOV 8.3 deg^2, -130°C, Exp time 45 sec, 19.3V limiting mag, Coverage 400 deg^2/hr, visits 4 obs per night.

Table 2 gives the following for LONEOS observations through Feb 2002: Discoveries 12,713, NEAs discovered 106, 45 months of operation.

§4.3 **Lowell Near-Earth Object Survey (LONEOS)** reads as follows:

“*The Lowell Near-Earth Object Survey (LONEOS) is run by Lowell Observatory (E. Bowell, B. Koehn) and utilizes a 0.59-m (f/1.0) modified Schmidt telescope located at the Lowell Anderson Mesa site near Flagstaff, Arizona. Two cryocooled 2048 × 4096 Marconi CCDs with 0.0135-mm, 2.4-arcsec pixels provide a total FOV of 8 deg^2. Using an unfiltered stare mode with 45-s integration, the system is capable of reaching V ~ 19.3 and can be run automatically.*

The system utilizes four visits, and moving-object detection is automatic, although the observer can visually inspect candidate objects in near real time and compute short-arc Vaisala orbits to identify possible NEAs.

The LONEOS approach of using a large-format CCD with large pixels and large FOV has been successful.

Future plans include a collaboration with scientists at the U.S. Naval Observatory Flagstaff Station using a new mosaic camera on their 1.3-m telescope, which should double the current LONEOS discovery rate. Even further in the future is the potential 4-m Next Generation Lowell Telescope with a 3.2-deg^2 FOV and V ~ 22.3.”

****

Appendix I. Bowell, Koehn, and Skiff (2008) Manuscript

11Mar08

The Lowell Observatory Near-Earth-Object Search (LONEOS): Ten years of asteroid and comet discovery

Edward Bowell, Bruce Koehn, and Brian Skiff

LONEOS has just completed a ten-year search for Earth-approaching asteroids and comets. So-called near-Earth Objects (NEOs) pose a long-term hazard to our planet. Past impact scars tell of many devastating impacts, some of which virtually snuffed out life on Earth. If there is no warning of future impacts, the risk to an individual in the U.S.A. is comparable to that of being involved in commercial plane crashes, floods, or tornadoes---threats our society takes very seriously. The first step in mitigating the NEO hazard is to make a census of the NEO population, and, where appropriate, carry out computations to assess the probability that a given NEO might strike the Earth in, say, the coming century. If no significant impacts are predicted, the NEO problem can be handed off to our grandchildren, who will draw upon much more powerful technology for their searches. If an Earth impact *is* predicted, then ways must be found to divert the NEO or otherwise minimize destruction on the ground, both of which problems are beyond the purview of astronomers.

Starting out

In 1992, Bowell and University of Helsinki astronomer Karri Muinonen, then at Lowell as a postdoctoral researcher, constructed a mathematical model to determine how many telescopes would be needed to search the skies, and for how long, to discover 90% of NEOs larger than 1 km in diameter---the threshold size for globally catastrophic impacts. The task looked daunting, because at the time no one had routinely succeeded in constructing the necessary wide field-of-view camera containing a mosaic of charge-coupled device (CCD) detectors. The resulting 1992 NASA Spaceguard Survey report called for six expensive 2.5-m telescopes to operate for a decade.

It turned out that the 1992 report was ahead of its time. By 1995, when a second NASA report on NEOs was written, mosaic CCD cameras were becoming larger, less expensive, and easier to manufacture; and the price of computers, needed to detect NEOs very quickly after images had been recorded, had tumbled. The 1995 effort was chaired by Gene Shoemaker, a Lowell Observatory and U.S. Geological planetary scientist who is acknowledged as the modern-day instigator of NEO impact studies. Then, in 1998, Congress directed that NASA take steps to discover 90% of NEOs larger than 1 km in diameter---the globally hazardous ones---within a decade. The 1998 start, dubbed the Spaceguard Survey, was timed to coincide with the advent of NEO search systems operated by several U.S. groups, including LONEOS (although one pioneering search, the Spacewatch Project, at the time led by Tom Gehrels at the University of Arizona, had automatically detected its first NEO in 1990).

Nuts and bolts

Lowell Observatory had acquired a 0.6-m f/1.8 Schmidt telescope from Ohio Wesleyan University in 1990, and by 1992 had secured funding from NASA to equip the focal plane with a 4-million pixel CCD camera, built by collaborators from the University of California, Santa Barbara, and Lawrence Livermore National Laboratory. The Schmidt telescope, built for photography, was given a very extensive facelift by mechanical designer Ralph Nye, and was equipped with modern electronics by Rich Oliver (figures 1, 2, and 3). For various reasons, progress in getting the telescope, its associated computers, and the software in working order was painfully slow---to the point that we thought funding might be cut off. We finally achieved first light in January 1998, though many of our first detected "asteroids" embarrassingly turned out to be artifacts in the CCD images. Subsequently, we equipped LONEOS with a Lowell-built 17-million pixel camera, designed by instrumentation specialist Ted Dunham, and Koehn (figure 4) greatly improved the moving-object detection software.

How was a small Schmidt telescope going to be an effective NEO discovery system, when a few years earlier a sextet of much larger telescopes was thought to be needed? There are two factors that lead to successful NEO detection. First, a wide field of view is needed so as to cover a large fraction of the accessible dark sky each month. Second, the CCD camera must be able to detect stars and moving objects to a faint limiting magnitude. Because LONEOS was capable of searching most of the accessible dark sky each month to a limiting magnitude of $V = 19.3$, the LONEOS system was actually well tuned to the discovery of the larger NEOs. That is exactly what the Spaceguard Survey was calling for.

A night at the LONEOS telescope

We attempted to operate LONEOS on every clear and partially clear night except for a few days around full Moon. Observing was carried out from a heated and relatively comfortable control room below the telescope (figure 5), and, once set up, the telescope, camera, and image analysis computers could run all night without manual intervention. Before observing, the observer created a sequence of telescope pointings, called a script, which was then used to control the telescope motion through the night. For optimum moving-object detection, each field was observed four times. Our standard exposure was 45 seconds, though each pointing took about 75 seconds, the "dead time" comprising readout of the CCD chips and the time taken to move the telescope from one field to the next. In practice, the telescope was cycled four times around a "block" of 10 to 20 contiguous fields before moving on to the next block. During the course of a winter night we could observe more than 100 different fields totaling about 1000 square degrees of sky (about twice the area of the constellation of Orion).

After a sequence of four images of a given field were acquired, two computers went to work to locate all the fixed stars and to identify all light sources that appeared to move, with the requirement that the latter move in very close to straight lines against the starry background. In principle, the observer could have gone home---and sometimes did---after the script had been written and the observing sequence started. However, we normally required the observer to stay awake and alert in the control room so as to assess the moving-object detections in near-real time. Now, about 97% of all moving-object detections were of main-belt asteroids, distant enough that they pose no threat to Earth. The remainder, automatically identified by their unusual motions, needed visual inspection to ascertain that they originated from celestial objects and were not artifacts such as the fragmented diffraction spikes of bright star images. Visual inspection was also used to distinguish comet from asteroid images (comet images usually exhibit fuzzy outlines). Then, after verifying that an unusually moving object was not previously known, the observer emailed its celestial coordinates to the Minor Planet Center (MPC) in Cambridge, Massachusetts, the International Astronomical Union's collection center and repository of asteroid and comet positional data. The entire process of NEO discovery and data transmission could take as little as 5 minutes, and in that regard we are proud to have been the fastest of the NEO search teams. Subsequently, the MPC disseminated ephemeris predictions to other observers worldwide (mostly amateurs) so the necessary follow-up observations could be made to determine the object's orbit and, if necessary, initiate computations (at the Jet Propulsion Laboratory in Pasadena, California, and at the University of Pisa, Italy) that would indicate whether there was a significant chance of collision with Earth.

Achievements

On long nights of good seeing, LONEOS was able to observe up to 6,000 asteroids, a handful of comets, and perhaps three or four previously unknown NEOs. To put that in perspective: at LONEOS's inception in 1998, there were only about 8,000 asteroids whose orbits were accurately known. Over LONEOS's ten years of operation, about 450,000 individual exposures of 130,000 regions on the sky were taken. The very large quantity of data resulting---about 15 terabytes---would, if it were words rather than images, amount to more than 20 million 300-page novels, about 30 times the print material in the Library of Congress. Today, we have enough computer storage that most of the imaging data can be contained on two suitcase-size server computers. Figures 6, 7, and 8 show examples of important LONEOS discoveries.

Brian Skiff was our chief observer, though Michael Van Ness and Bruce Koehn also spent many nights at the telescope. Eleven additional individuals, most of them summer students, were able to discover at least one NEO each.

We now know that there are about 1,000 near-Earth asteroids (NEAs) larger than 1 km in diameter, and, to date, about 800 of them have been discovered. In total, LONEOS was responsible for the discovery of 289 NEAs and 42 comets. About 55 of the LONEOS NEAs are thought to be larger than 1 km in diameter. Interestingly, if LONEOS had not had to share the search for NEOs with four additional NASA-funded groups, we would have discovered more than 1,300 NEAs, almost 500 of them larger than 1 km in diameter. Thus, LONEOS would, if not in (friendly) competition with the other groups, have been able to complete about half the Spaceguard Survey by itself.

Of course, the vast majority of LONEOS's asteroid discoveries were main-belt asteroids, which orbit the Sun harmlessly between the orbits of Mars and Jupiter. When asteroids of all kinds have been well enough observed that they are unlikely ever to be lost, they are given permanent numbers. Currently, LONEOS is fourth in the ranking of numbered asteroid discoveries, with 10,974 out of a total of 178,283. As more of our discoveries become well observed, LONEOS's haul of numbered asteroids will increase further.

LONEOS's imaging data will remain valuable---and not just to planetary scientists---as a decade-long record of events over much of the sky. For example, because we observed some regions of the sky more than 100 times, our data can be used to look for changes in the brightness of stars. Our collaboration with Antonino Micelli (University of Washington) and others has resulted in a major study of RR Lyrae variable stars in our galaxy. From a 15-month span of LONEOS data, Micelli et al. discovered 838 RR Lyrae stars, from which they were able to suggest that the spherical halo of material enveloping our galaxy was formed by at least two distinct processes of accretion.

What next?

If, as seems likely, we can be reasonably sure that no kilometer-size NEO is going to strike the Earth in the coming century, then we will have assessed about 90% of the total NEO hazard to our planet (though note that the long-term hazard will remain unchanged). The remaining risk, 10% of what it was before the Spaceguard Survey, will be from yet-to-be-discovered NEOs. In 2003, computations were made showing that if 90% of NEOs larger than 140 m in diameter could be discovered, we would be able to assess as much as 99% of the total NEO risk. Clearly, larger instruments than the meter-class telescopes used for the Spaceguard Survey would be required to extend the search down to 140-m NEOs, perhaps in one to two decades. But how big? The answer appears to be several 4-m class telescopes or a combination of ground-based telescopes and a space-based telescope, the latter either in low Earth orbit or in an orbit similar to Venus's.

At least three wide-field telescopes capable of contributing to the extended NEO search are under construction now. The University of Hawaii's Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) consists of a 1.8-m telescope and the world's largest mosaic CCD camera. It is planned to yoke together four such telescopes to form the equivalent of a 3.6-m wide-field imager. Lowell Observatory's 4.2-m Discovery Channel Telescope, due to see first light in 2011, could also contribute to the NEO search. However, although plans exist for a wide-field camera with a performance close to that of Pan-STARRS, funding for the camera has not yet been found. The Large Synoptic Survey Telescope, to be located in Chile, will be the granddaddy of wide-field survey telescopes. With an 8.4-m primary mirror, and a camera capable of imaging 10 square degrees at a time, LSST will by itself be capable of carrying out the extended NEO search down to 140-m diameter objects.

But is the extended NEO search worth conducting? The current Spaceguard Survey of 1-km diameter and larger NEOs will have cost about $40 million and will have "retired" about 90% of the impact risk. Retiring an additional 9% of the risk will cost at least $400 million; that is, 100 times as much per percent assessment of risk. Recall that, before the Spaceguard Survey was started, one's risk of being killed by an NEO impact was thought to be comparable to that of perishing in a commercial plane crash. It is now thought to be ten times less, perhaps as dangerous as venomous bites or fireworks accidents. The extended NEO search will likely reduce the risk to that of succumbing to food poisoning. However, we will always have a question: Will we really have found almost all the potentially dangerous NEOs or could there still be an undiscovered one with our name on it? For example, could there be a comet coming in from the Oort Cloud on an Earth-impact trajectory? Even with anticipated survey technology improvements, we could only expect about one year's warning as the comet became active, and therefore bright enough to detect, at about the distance of Jupiter. We leave it to you to figure out whether our nation should spend half a billion dollars to achieve the next level of celestial "security".

Figures

Figure 1. Ted Bowell stands next to the LONEOS telescope, under construction in 1996.

Figure 2. The LONEOS Schmidt telescope as it is today.

Figure 3. The LONEOS dome under a starry sky at Anderson Mesa, Lowell Observatory's dark-sky site (photo courtesy Jeremy Perez).

Figure 4. Bruce Koehn, who created almost all the software used to operate LONEOS and to analyze its data.

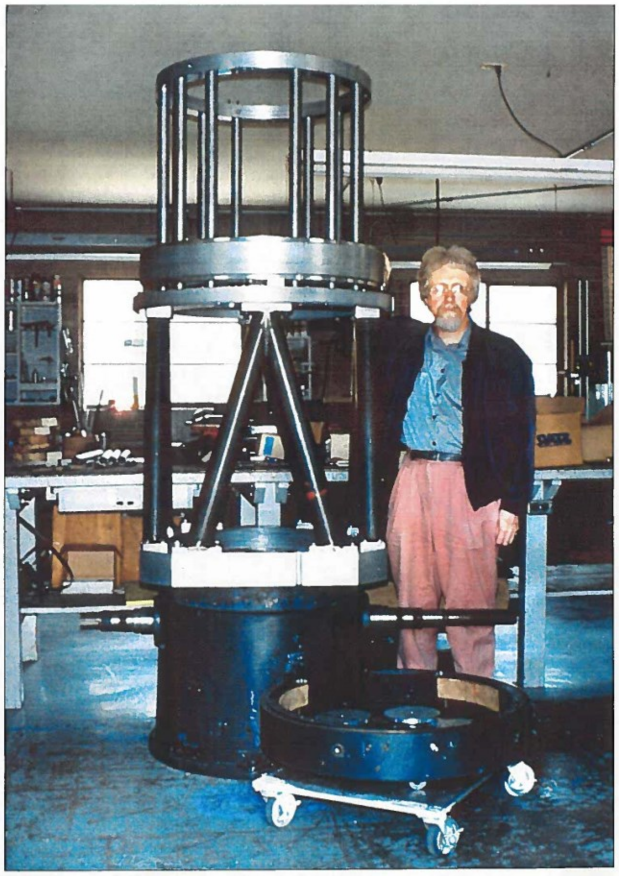
Figure 5. Brian Skiff in the LONEOS control room (photo courtesy Jeremy Perez).

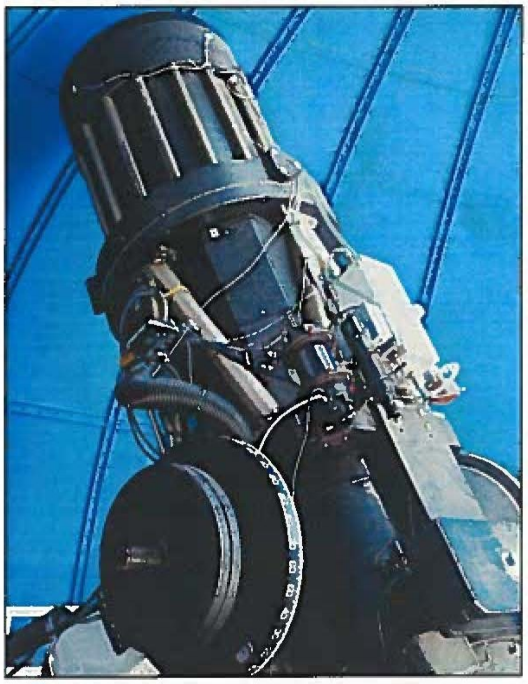
Figure 6. NEA 2003 SQ_{222}, missed by our detection software because it was moving very fast, was discovered on September 28, 2003, by volunteer Robert Cash (of Minor Planet Research, Inc.). The three panels show its motion (the asteroid's trailed images are circled in green) against the stars over the course of 41 minutes. The total motion is 34 arcminutes, a little more than the diameter of the Moon. On the day before discovery, 2003 SQ_{222} had passed just one fifth of the Moon's distance from Earth. If 2003 SQ_{222} one day collides with Earth, it will burn up harmlessly in the atmosphere, being just the size of a small house.

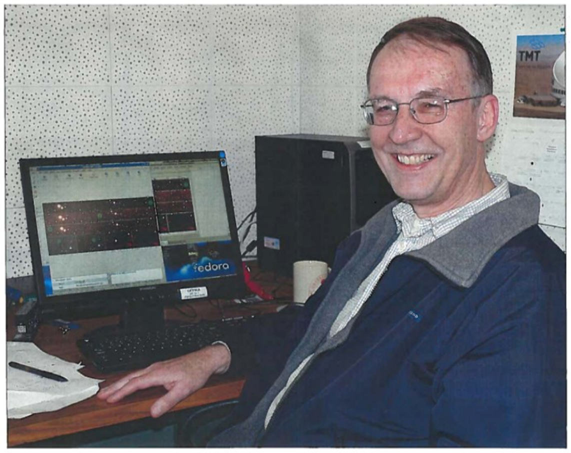
Figure 7. On October 15, 2003, Brian Skiff discovered a relatively bright fast-moving asteroid that, once its orbit had been determined, turned out to be the NEA Hermes, lost since its discovery in 1937. Because Hermes had approached Earth within twice the Moon's distance in 1937, it was thought to be hazardous to Earth. However, post-

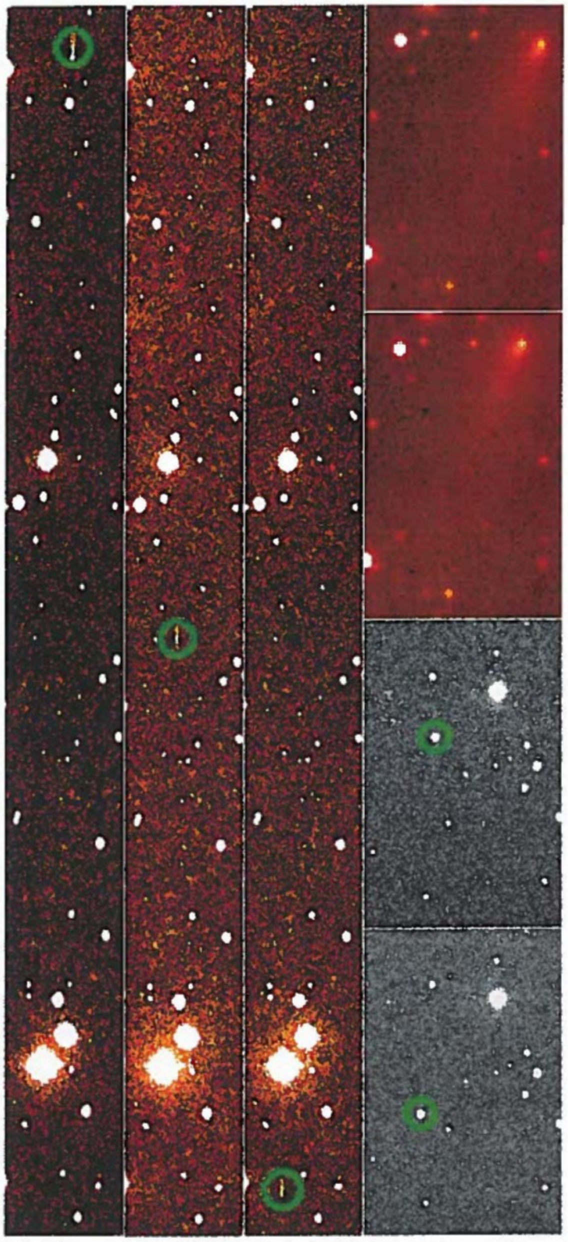
recovery orbit computations proved that that Hermes is harmless. Radar observations showed that Hermes consists of two 300-m bodies orbiting each other at a distance of 1.2 km.

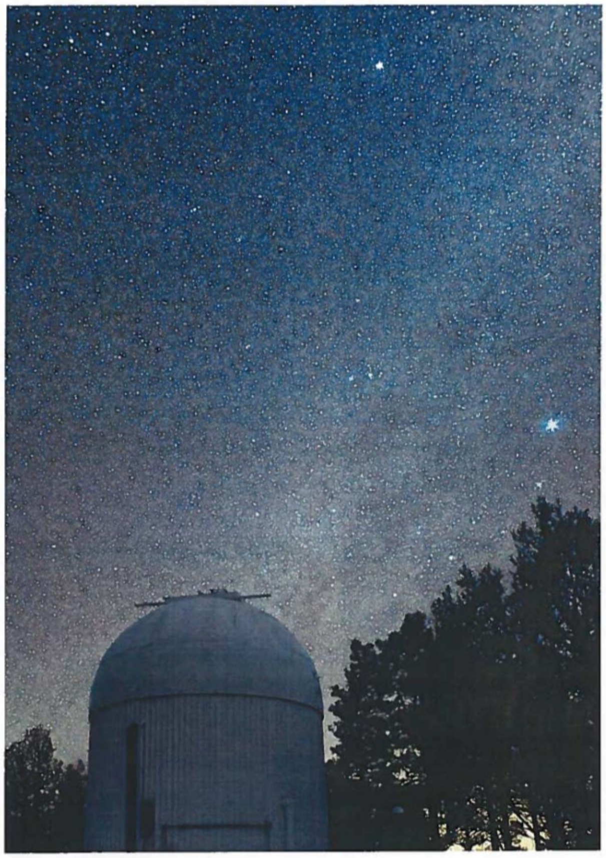
Figure 8. Comet P/2005 R_2 (Van Ness) was discovered by Michael Van Ness on September 10, 2005. Relatively bright ($V = 17$ mag) for a newly discovered comet, the LONEOS images show a coma 20 arcseconds in diameter and a fan-shaped tail 4 arcminutes long. This periodic comet should become visible again in 2011.











http://www.perezmedia.net/beltofvenus/archives/images/2007/img20070215_LONEOSS1m... 3/6/2008

http://www.perezmedia.net/beltofvenus/archives/images/2005/img2005103000_02.jpg 3/6/2008