Long-term Near-infrared Brightening of Nonvariable OH/IR Stars

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Abstract

Nonvariable OH/IR stars are thought to have just left the asymptotic giant branch (AGB) phase. In this conventional picture, they must still show strong circumstellar extinction caused by the dust ejected during the AGB phase, and the extinction is expected to decrease over time because of the dispersal of the circumstellar dust after the cessation of stellar mass loss. The reduction of extinction makes the stars become apparently brighter and bluer with time, especially in the near-infrared (NIR) range. We look for such long-term brightening of nonvariable OH/IR stars by using 2MASS, UKIDSS, and OAO1WFC survey data. As such, we obtain multiepoch NIR data taken over a 20 yr period (1997–2017) for 6 of 16 nonvariable OH/IR stars, and all 6 objects are found to be brightening. The K-band brightening rate of five objects ranges from 0.010 to 0.130 mag yr\(^{-1}\), which is reasonably explained with the conventional picture. However, one OH/IR star, OH 31.0\,-, shows a rapid brightening, which cannot be explained only by the dispersal of the dust shell. Multicolor (J-, H-, and K-band) data are obtained for three objects, OH 25.1–0.3, OH 53.6–0.2, and OH 77.9+0.2. Surprisingly, none of them appears to have become bluer, and OH 53.6–0.2 is found to have reddened at a rate of 0.013 mag yr\(^{-1}\) in (J – K). Our findings suggest other mechanisms such as rapid changes in stellar properties (temperature or luminosity) or a generation of a new batch of dust grains.

Unified Astronomy Thesaurus concepts: Asymptotic giant branch stars (2100); Post-asymptotic giant branch stars (2121); Stellar evolution (1599); Late-type stars (909); Stellar mass loss (1613); Circumstellar matter (241)

1. Introduction

The asymptotic giant branch (AGB) phase is a late evolutionary phase of low- and intermediate-mass stars with main-sequence masses of \(\sim 1–10\ M_\odot\) (Habing 1996; Herwig 2005; Karakas & Lattanzio 2014). The stars in this phase show significant variability caused by stellar pulsation and mass ejection. Dust grains are created in mass-loss winds, and consequently, the circumstellar dust shell is developed around the central AGB stars. Among AGB stars, more massive and more evolved AGB stars are thought to experience stronger mass loss, resulting in the optically thicker dust shell causing greater obscuration of the central star (Vassiliadis & Wood 1993; Blöcker 1995a; Ferrarotti & Gail 2006).

OH/IR stars are believed to be such objects undergoing the heaviest mass loss. The name OH/IR indicates that this kind of objects shows OH maser emission at 1612 MHz and are bright in the infrared rather than the optical (Habing 1996). These characteristics arise from a thick circumstellar shell created by massive mass-loss winds. In addition, these objects show long-period variability with periods from several hundred to over a thousand days (Engels et al. 1983; Herman & Habing 1985; Habing 1996). Such a long-period variability is also expected for the evolved stars, which are larger but less massive (Vassiliadis & Wood 1993). These pieces of evidence support the hypothesis that OH/IR stars are evolved AGB stars.

On the other hand, some OH/IR stars are known to have no or little variability, and they are called nonvariable OH/IR stars. The variability of OH/IR stars is often investigated through OH maser emission, because their variability is difficult to monitor in the optical. Such nonvariable OH/IR stars were discovered by Herman & Habing (1985). They monitored the OH maser emissions of bright OH/IR stars selected from Baud’s catalog (Baud et al. 1981) to evaluate their variability and found that 25% of their targets showed no or little variability.

Such a nonvariability is expected to occur after the end of AGB mass loss. In the transition from the AGB phase to the following post-AGB phase, the significant pulsational variability and heavy mass ejection of the central star are thought to cease, because these characteristics are not observed from post-AGB stars (e.g., Vassiliadis & Wood 1994; Blöcker 1995b). As a result, the circumstellar dust shell starts to dissipate, and the central star obscured in the AGB phase gradually brightens in the optical and near-infrared (NIR). This reappearance of the stellar emission in the NIR has been suggested from spectral energy distribution (SED) analyses. Engels (2007) found that some nonvariable OH/IR stars showed NIR excess while normal OH/IR stars did not show such an NIR excess. This NIR excess was interpreted as the emission from the star that was reemerging from the optically thick dust shell. This result suggests that the nonvariable OH/IR stars are in transition from the AGB phase to the post-AGB phase. Bedijn (1987) also supported this picture from mid- to far-infrared SED modeling.
He reported that nonvariable OH/IR stars dominated a region in the IRAS two-color diagram (log [\(\lambda F_\lambda(25)/\lambda F_\lambda(12)\)] \(\geq 0.2\), log [\(\lambda F_\lambda(60)/\lambda F_\lambda(25)\)] \(\sim -0.6\)–0.1) and their colors could be reproduced by models with a dispersing dust shell after the cessation of AGB mass loss.

These studies were based on one-epoch observations, but now, we can investigate the long-term brightness evolution of these objects by using infrared archival data. In this paper, we investigate the long-term NIR (the J-, H-, and K-band) brightness evolution of nonvariable OH/IR stars to reveal their real-time evolution. Data in wavelength regions longer than the K band are also useful especially to investigate the evolution of the thermal emission from the circumstellar dust shell. However, the treatment of the thermal emission from the dust shell requires the detailed modeling of radiative-transfer processes, which is beyond our scope. Therefore, we focus on only the NIR evolution in this paper. Below, in Section 2, we describe the target identification by searching for infrared counterparts of nonvariable OH/IR stars. The search method for the long-term brightness evolution using NIR archival data is described in Section 3. Section 4 shows the results, and we discuss the origin of the observed brightness evolution in Section 5. Section 6 summarizes this study.

### 2. Target Identification

The targets are selected from the list of OH/IR stars monitored by Herman & Habing (1985). They measured the variability amplitude of OH maser emission in radio magnitude, which is defined as the logarithm of the peak maser flux density. We select 16 OH/IR stars with variability amplitudes less than 0.3 as nonvariable OH/IR stars. They are listed in Table 1.

At first, we determine their precise coordinates by finding bright infrared objects in images taken with the Spitzer Space Telescope (SST; Werner et al. 2004). OH/IR stars are sometimes invisible even in the NIR because of heavy obscuration by the circumstellar dust but are very bright in the thermal infrared (TIR) beyond the NIR. Therefore, high-resolution TIR images are useful to determine the precise coordinates of OH/IR stars (e.g., Deguchi et al. 2007; Engels 2007). We use TIR images of the target nonvariable OH/IR stars taken with the Infrared Array Camera (IRAC; Fazio et al. 2004) on board the SST. The SST data are now easily retrievable from the Spitzer Enhanced Imaging Products (SEIP) database on the NASA/IPAC Infrared Science Archive (IRSA). As all of the targets are found near the galactic plane, the IRAC images and source list made available by the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) project are useful for the target identification. We look for infrared-bright objects in the IRAC images. The results are shown in Table 1 and Figure 1. Except for the following three objects, OH 1.5–0.0, OH 15.7+0.8, and OH 31.0–0.2, infrared counterparts are found close to the positions given by SIMBAD. The results are summarized as follows.

**OH 0.3–0.2:** A bright object is clearly found in the IRAC band 4 image (8.0 \(\mu m\)) at the SIMBAD position, while in the

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**Notes.**

* a Names used by Herman & Habing (1985).

* b OH 001.484–00.061 is regarded as OH 1.5–0.0 (see text for details).

* c More precisely, 0\(^{h}\)7 northwest from the GLIMPSE position (see text for details).

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### Table 1

**Names and Positions of the Target Nonvariable OH/IR Stars**

| Object Name\(^a\) | 2MASS Name | SSTGLMC Name | R.A. (deg; J2000) | Decl. (deg; J2000) | Position Source |
|-----------------|------------|-------------|------------------|-------------------|-----------------|
| OH 0.3–0.2      | G000.3335  | GLIMPSE     | 266.77896        | -28.74976         | GLIMPSE         |
| OH 1.5–0.0      | G001.4837  | GLIMPSE     | 267.33709        | -27.69849         | GLIMPSE         |
| OH 11.5–0.1     | J18103867–1852583 | GLIMPSE | 272.66118       | -18.882896       | GLIMPSE         |
| OH 15.7+0.8     | G015.7010+0.7705 | GLIMPSE | 274.107406      | -14.920483       | GLIMPSE         |
| OH 17.7–2.0     | J18303070–1428570 | GLIMPSE | 277.627928       | -14.482512       | 2MASS           |
| OH 18.3–0.4     | G018.2956+0.4291 | GLIMPSE | 275.679577       | -12.794966       | GLIMPSE         |
| OH 18.5+1.4     | J18193549–1208081 | GLIMPSE | 274.897885       | -12.135602       | GLIMPSE         |
| OH 18.8+0.3     | G018.7687+0.3016 | GLIMPSE | 276.022247       | -12.436756       | GLIMPSE         |
| OH 25.1–0.3     | J18381546–0709543 | GLIMPSE | 279.564387       | -07.165077       | GLIMPSE         |
| OH 31.0–0.2     | G030.9439+0.0351 | GLIMPSE | 281.921407       | -01.753168       | GLIMPSE         |
| OH 31.0–0.2     | G031.0123+0.2193 | GLIMPSE | 282.179217       | -01.808404       | GLIMPSE         |
| OH 37.1–0.8     | G037.1184–0.8473 | GLIMPSE | 285.526137       | +03.37738        | GLIMPSE         |
| OH 51.8–0.2     | J19274203+1637239 | GLIMPSE | 291.925188       | +16.623349       | GLIMPSE         |
| OH 53.6–0.2     | J19312537+1813103 | GLIMPSE | 292.855788       | +18.219504       | GLIMPSE         |
| OH 77.9+0.2     | J20283067+3907009 | GLIMPSE | 307.127821       | +39.116924       | 2MASS           |
| OH 359.4–1.3\(^c\) | G359.3798–01.2008 | GLIMPSE | 267.216181       | -30.088645       | GLIMPSE         |

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8. https://irsa.ipac.caltech.edu/frontpage/  
9. https://irsa.ipac.caltech.edu/irsaviewer/  
10. http://simbad.u-strasbg.fr/simbad/
other images, another object is found in the northeast direction from the SIMBAD position. The previous object becomes fainter in shorter wavelengths, and the latter object gets brighter than the previous object in shorter wavelengths. We identify the previous object, SSTGLMC G000.3335−00.1805 in the GLIMPSE catalog, as OH 0.3−0.2 because of the redness and brightness in the TIR and the positional agreement with SIMBAD.

OH 0.3−0.2 is also listed as OH 0.335−0.180 in the SIMBAD database. The NIR spectrum of OH 0.335−0.180 is reported by Vanhollebeke et al. (2006). However, according to the observed position in their log (Table A.3 in Vanhollebeke et al. 2006), the reported object seems to be a different object, 2MASS J17470734−2844282, brightly seen at the north edge of the 2MASS H-band image in Figure 1.

**OH 1.5−0.0 (OH 001.484−00.061):** Because this object is recorded without coordinates in the SIMBAD database, we searched for an OH/IR star around \((l, b) = (1°5, −0°0)\) in the OH maser source catalog created by Sevenster et al. (1997) and found OH 001.484−00.061 as the only object around the position. Therefore, we regard OH 001.484−00.061 as OH 1.5−0.0 and adopt the position of OH 001.484−00.061 as the initial position for OH 1.5−0.0. A bright infrared object, SSTGLMC G001.4837−00.0612, is found at this position, while the 2MASS images only show another object named 2MASS J17492131−2741555 in the east direction. This suggests that SSTGLMC G001.4837−00.0612 has very red color in the NIR. Based on the positional agreement, red color, and TIR brightness, we identify SSTGLMC G001.4837−00.0612 as OH 1.5−0.0.

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**Figure 1.** (a) 2MASS and IRAC images of the identified objects. These images are retrieved from the IRSA viewer service. The images are shown in logarithmic scale. The grayscale range is adjusted for better visibility. The positions written in Table 1 are shown with cross marks in center. Horizontal and vertical axes show the RA and Dec offsets from those positions, respectively. The positions initially checked based on SIMBAD are shown with open squares. For OH 1.5−0.0, the square mark shows the position of OH 001.484−00.061 listed by Sevenster et al. (1997; see text for details). (b) 2MASS and IRAC images of the identified objects.
**OH 11.5+0.1:** A very bright infrared object is found in both 2MASS and IRAC images at the SIMBAD position. It is 2MASS J18103867−1852583 and SSTGLMC G011.5599+00.0873 in the 2MASS PSC and the GLIMPSE catalog, respectively. We identify this object as OH 11.5+0.1.

**OH 15.7+0.8:** There is an object at the SIMBAD position clearly seen in the 2MASS images. However, there are much brighter objects in the vicinity of the SIMBAD position in the IRAC images. This object at the SIMBAD position of OH 15.7+0.8 is therefore rather blue, and hence, is unlikely to be an OH/IR star. The reddest object in the vicinity of the SIMBAD position is thus the object at 6″ east of the SIMBAD position, which we consider to be OH 15.7+0.8. This object is cataloged as SSTGLMC G015.7010+00.7705 in the GLIMPSE catalog. IRAS 18135−1456 is listed as an alternative name of OH 15.7+0.8 in SIMBAD. Its NIR spectrum is reported by Oudmaijer et al. (1995). However, the target coordinate listed in their Table 1 corresponds to the position of a different object, 2MASS J18162412−1455138, seen 18″ west from the SIMBAD position (out of the image in Figure 1). Therefore, the spectrum reported by Oudmaijer et al. (1995) is probably not of OH 15.7+0.8.

**OH 17.7−2.0:** A pair of bright objects is seen in the 2MASS images at the position of OH 17.7−2.0 given by SIMBAD. SIMBAD suggests that OH 17.7−2.0 is the southeast object of the pair, which corresponds to 2MASS J18303070−1428570. A bright object is found at the same position in the IRAC images retrieved from SEIP, and not listed in the GLIMPSE catalog. Therefore, we identify 2MASS J18303070−1428570.
as OH 17.7−2.0 and use the 2MASS position as the target position.

**OH 18.3+0.4:** At the SIMBAD position, a bright object is seen only in the IRAC images. This is SSTGLMC G018.2956+00.4291 in the GLIMPSE catalog. Based on the absence of the object in the 2MASS images, this object is very red, which is a usual characteristic of OH/IR stars. Therefore, we identify this object as OH 18.3+0.4.

**OH 18.5+1.4:** One bright object is seen in both 2MASS and IRAC images. This is listed as 2MASS J18193549−1208081 and SSTGLMC G018.5182+01.4129 in the 2MASS PSC and the GLIMPSE catalog, respectively. We identify this object as OH 18.5+1.4.

**OH 18.8+0.3:** In the IRAC images, a bright red object is found at the SIMBAD position, while no object is seen in the 2MASS images. We identify this red object, SSTGLMC G018.7687+00.3016 in the GLIMPSE catalog, as OH 18.8+0.3.

**OH 25.1−0.3:** A bright red object is found in both the 2MASS and IRAC images at the SIMBAD position. This object is 2MASS J18381546−0709543 and SSTGLMC G025.0568−00.3505 in the 2MASS PSC and the GLIMPSE catalog, respectively. This object is thought to be OH 25.1−0.3.

**OH 31.0+0.0:** A bright red object is found at the SIMBAD position in the IRAC images, while no object is found in the 2MASS images. The object is cataloged as SSTGLMC G030.9439+00.0351 in the GLIMPSE catalog. We identify this object as OH 31.0+0.0.

**OH 31.0−0.2:** No object is found at the SIMBAD position of OH 31.0−0.2 in both 2MASS and IRAC images. However, we find a bright red object 10\" northeast of the SIMBAD position in the IRAC images. We identify this object, listed as SSTGLMC G031.0123−00.2193 in the GLIMPSE catalog, as OH 31.0−0.2.

**OH 37.1−0.8:** A bright red TIR object is seen in the IRAC images at the SIMBAD position. This object is listed as SSTGLMC G037.1184−00.8473 in the GLIMPSE catalog. We identify this object as OH 37.1−0.8 based on the redness and brightness in the TIR. In the 2MASS images, this object is not seen, while a different object is seen in the west. This is 2MASS J19020603+0320170. We note that this 2MASS object is not OH 37.1−0.8.

**OH 51.8−0.2:** A bright red TIR object is found in the IRAC images. This is SSTGLMC G051.8038−00.2248 in the GLIMPSE catalog. This object is faintly seen in the 2MASS Ks-band image and listed as 2MASS J19274203+1637239 in the 2MASS PSC. We identify this object as OH 51.8−0.2.

**OH 53.6−0.2:** One bright object is seen in all the 2MASS and IRAC images. This is 2MASS J19312537+1813103 and SSTGLMC G053.6303−00.2392 in the 2MASS PSC and the GLIMPSE catalog, respectively. We identify this object as OH 53.6−0.2.

**OH 77.9+0.2:** One bright red object is seen in all the 2MASS and IRAC images. This object is listed in the 2MASS catalog as 2MASS J20283067+3907009 but not listed in the GLIMPSE catalog. Therefore, we use the position of 2MASS J20283067+3907009 as the target position.

**OH 359.4−1.3:** A bright TIR source is found in the IRAC band 4 image 0\"7 northwest of the GLIMPSE catalog position of SSTGLMC G359.3798−01.2008 (Table 1, Figure 1). This TIR source coincides well with OH 359.380−01.201, the only OH maser source in the vicinity (Sevenster et al. 1997). The positional offset between this TIR source and the OH maser source is 0\"3, within the positional accuracy of the respective data (0\"; Spitzer Science 2013: 0\"; Sevenster et al. 1997). Hence, we regard this TIR object as the OH maser source. The UKIDSS K-band image at a higher spatial resolution shows two marginally resolved objects, the brighter one 0\"6 east and the fainter one ~0\"6 northwest of the SSTGLMC G359.3798−01.2008 catalog position (Figure 2; also see the next section). Therefore, we consider the fainter of the two NIR objects in the UKIDSS K-band image as the TIR/OH maser source, i.e., OH 359.4−1.3.

### 3. Archival Data Analysis

The long-term brightness evolution of the nonvariable OH/IR stars is examined with the 2MASS PSC, UKIRT Infrared Deep Sky Survey (UKIDSS) data, and data taken with the Okayama Astrophysical Observatory Wide Field Camera (OAOWFC; Yanagisawa et al. 2019). Three stars in our sample, OH 0.3−0.2, OH 1.5−0.0, and OH 359.4−1.3, are included in the observation area of the Vista Variables in the Via Láctea (VVV) survey (Minniti et al. 2010). However, we do not find their photometric data in the VVV Data Release 4 (DR4). Therefore, we use only 2MASS, UKIDSS, and OAOWFC data in this study.

As shown in Table 1, seven objects are listed in the 2MASS catalog. Their NIR magnitudes from 1997 to 2001 can be investigated by using the 2MASS catalog. However, the J-, H-,
and $K_S$-band magnitudes of OH 17.7−2.0 are not reliable because they have a quality flag of U or E. OH 51.8−0.2 has a reliable $K_S$-band magnitude with a quality flag of B, while its $J$- and $H$-band magnitudes have a quality flag of U and are unreliable. Other objects have reliable $J$-, $H$-, and $K_S$-band magnitudes with a quality flag of A or B. The 2MASS catalog gives the total photometric error including not only measurement errors but also systematic errors such as calibration and flat errors as [jhk]$_{\text{msigcom}}$ (Cutri et al. 2006). We employ [jhk]$_{\text{msigcom}}$ as the photometric error. We can also get precise observation dates from the catalog.

The UKIDSS project is described by Lawrence et al. (2007). UKIDSS uses the UKIRT Wide Field Camera (WFCAM; Casali et al. 2007) and a photometric system described by Hewett et al. (2006). The pipeline processing and science archive are described by Irwin et al. (2004) and Hambly et al. (2008). In the UKIDSS data, the target objects are observed in the Galactic Plane Survey (GPS; Lucas et al. 2008). In the GPS program, the north galactic plane $|b| < 5^\circ$ in $l = 15^\circ$−107$^\circ$, 142$^\circ$−230$^\circ$, $|b| < 2^\circ$ in $l = -2^\circ$ to $+15^\circ$ was surveyed by the UKIRT 3.8 m telescope once in the $J$ and $H$ bands and twice in the $K$ band from 2005 to 2012. We use the source catalog and images opened in the 11th data release (DR11PLUS), which is available from the WFCAM Science Archive (WSA; Hambly et al. 2008) website.\footnote{http://wsa.roe.ac.uk/index.html}

Figure 2 shows the UKIDSS images. Among the 16 targets, 13 objects except for OH 0.3−0.2, OH 1.5−0.0, and OH 18.3 +0.4 are found in the UKIDSS images. OH 18.8+0.3 and OH 359.4−1.3 are detected in the UKIDSS images but are not listed in the GPS catalog. Therefore, only 11 objects have photometric data in the GPS catalog. Three of 11 objects, OH 11.5+0.1, OH 17.7−2.0, and OH 18.5+1.4, have unreliable magnitudes because of saturation. The other eight objects have reliable magnitudes with error bits, pErrBits, less than 256, which is a criteria to select good-quality data, the same as used by Hambly et al. (2008). Various photometric magnitudes measured with different sizes of aperture photometry are listed in the database. Among the magnitudes, AperMag3, the photometric magnitude measured with an aperture diameter of 2″, is the default magnitude in the catalog (Lucas et al. 2008). We adopt this AperMag3 magnitude in this study. Uncertainties are also available in the database as AperMag3Err. However, according to Lucas et al. (2008), this error is usually underestimated because it does not take into account systematic calibration errors. Such systematic errors were evaluated by Hodgkin et al. (2009). They evaluated the repeatability of photometric measurements and concluded that an accuracy of 1%−3% could be achieved by applying appropriate corrections even under thin clouds. Therefore, in this study, we estimate the total photometric error by calculating the square root of the sum of squares (SRRS) of the measurement error (AperMag3Err) and 0.03 magn calibration error. The observation dates are obtained from the header of the FITS data for each target retrieved from the WSA website.

The OAOWF is an NIR camera developed by modifying the 0.91 m telescope at the Okayama Astrophysical Observatory (OAO). The OAOWF has been dedicated to a galactic plane monitoring survey in the $K_S$ band since 2015. The survey region is $|b| < 1^\circ$ in $l = 21^\circ$−36$^\circ$ and 75°−85°. Two of the 16 targets, OH 25.1−0.3 and OH 77.9+0.2, are found in the survey data. After basic reduction steps such as dark subtraction, flat correction, and World Coordinate System (WCS) matching, instrumental magnitudes are measured by the Source Extractor (SExtractor; Bertin & Arnouts 1996) and calibrated by comparing the 2MASS $K_S$-band magnitudes.

In order to compare the magnitudes obtained by different instruments, a system-conversion process must be applied. For the UKIDSS-GPS data, the system conversion was discussed by Hodgkin et al. (2009). However, they investigated the system-conversion equation only in a blue region, where the 2MASS $(J - K_S)$ color, $(J - K_{\text{2MASS}})$, is 0−1 mag. To deal with our red targets with $(J - K_{\text{2MASS}}) = 1.1-4.2$ mag, we define our own system-conversion relation appropriate for red objects by using 2MASS and UKIDSS-GPS data. We cross-match objects in the Galactic center region $|b| < 1^\circ$ and $|b| < 1^\circ$ listed in the 2MASS PSC (with quality flags of A, B, and C) and UKIDSS-GPS catalog (with magnitudes greater than 10 mag to avoid saturation) by using the CDS X-Match service\footnote{http://cdsxmatch.u-strasbg.fr/} with a search radius of 0.1°.

The results of the cross-matching are shown in Figure 3 as plots of the difference of the JHK magnitude between the two systems as a function of the corresponding 2MASS color. The gray dots are the data taken from the UKIDSS-GPS and 2MASS catalogs, and the black points and bars show the averages and standard deviations calculated in each 0.2 magnitude bin. The difference between 2MASS and OAOWF systems is very large. To deal with this difference, we derive a new system-conversion relation that covers red color regions. To cover red regions, data taken in three fields in the galactic plane are used, because red objects are obscured by interstellar dust exist in the galactic plane. After the basic calibrations, the systematic $K_S$-band magnitude difference against $(J - K_{\text{2MASS}})$ is examined. In this process, data with large photometric error (>0.05 mag) are removed. Data that have significant magnitude differences between 2MASS and OAOWF data (larger than five times the photometric error) are also removed as unreliable data. The result is shown in Figure 4. The derived relation shows that the difference between 2MASS and OAOWF systems is very small as shown by Yanagisawa et al. (2019). The OAOWF magnitudes are corrected to WFCAM magnitudes by using both this relation and the relation between the WFCAM and 2MASS systems derived above.

4. Results

NIR multiepoch data are established for seven objects, OH 15.7+0.8, OH 25.1−0.3, OH 31.0−0.2, OH 37.1−0.8, OH 51.8−0.2, OH 53.6−0.2, and OH 77.9+0.2. They are summarized in Table 2. The table shows the object names; $J$-, $H$-, and $K$-band magnitudes (where appropriate); observation dates; and data sources. All of the magnitudes except for
the $K$-band magnitude of OH 51.8−0.2 cannot be converted to WFCAM magnitude, because it does not have the $(H-K_S)_{\text{2MASS}}$ data required for the system conversion. Therefore, we can correctly examine NIR variability only for six objects except for OH 51.8−0.2.

Table 2 also shows the rate of change of the magnitude in the last column. The rate of change for the UKIDSS observations are derived by dividing the magnitude difference with the time interval between the first-epoch 2MASS or UKIDSS observation and the second-epoch UKIDSS observation. In the $J$ band, the apparent brightening is found in OH 25.1−0.3, OH 53.6−0.2, and OH 77.9+0.3 with significances of $1\sigma$−$2\sigma$. In the $H$ band, the apparent brightening is detected for OH 25.1−0.3, OH 53.6−0.2, and OH 77.9+0.3 at the $1\sigma$, $3\sigma$, and $5\sigma$ levels, respectively. The $K$-band brightening observed between 2MASS and UKIDSS observations is of $>3\sigma$ significance. OH 25.1−0.3, OH 53.6−0.2, and OH 77.9+0.2 are observed three times in 2MASS and UKIDSS observations, and the apparent brightening found in each of the two consecutive intervals is consistent within the uncertainties.

As for OH 51.8−0.2, the difference of the $K$-band magnitude is +0.139 (i.e., darkening) between the first-epoch 2MASS observation and the second-epoch UKIDSS observation without the system conversion. As shown in Figure 3, the differences between the $K$-band magnitudes of the 2MASS and UKIDSS observations are small, $-0.037$ to $+0.030$ mag in the whole $(H-K_S)_{\text{2MASS}}$ range. If we evaluate the total uncertainty on the magnitude change as the SRSS of this system-conversion uncertainty and the photometric uncertainties of the 2MASS and UKIDSS observations, it is calculated to be 0.138−0.140 mag. Therefore, it is difficult to conclude if OH 51.8−0.2 is darkening with a reasonable amount of certainty.

For OAOWFC data, the rate of change in Table 2 is derived by linear fitting of the OAOWFC monitoring data shown in Figure 6. Figure 6 shows the long-term variations of the $K$-band magnitude for the two nonvariable OH/IR stars, OH 25.1−0.3 and OH 77.9+0.2 (black plots), together with nearby reference stars (gray plots). Some OAOWFC data whose measured magnitudes sensitively change depending on the photometric aperture size are removed as unreliable data. The reference stars are selected with the criterion that the star is seen in the proximity of the target with a $K$-band magnitude close to that of the target. For OH 25.1−0.3, 2MASS J18381571−0710026 is
Table 2
Multiepoch Data Obtained from 2MASS, UKIDSS, and OAwF data

| Object Name | Band Name | Julian Date | Magnitude$^a$ (mag) | Data Source | Rate of Change$^b$ (mag yr$^{-1}$) |
|-------------|-----------|-------------|---------------------|-------------|----------------------------------|
| OH 15.7+0.8 | K         | 2453887.0115 | 15.644 ± 0.104      | UKIDSS      | −0.130 ± 0.019                   |
| OH 25.1−0.3 | J         | 2451363.6290 | 14.880 ± 0.034      | UKIDSS      | −0.029 ± 0.016                   |
|             |           | 2453892.9832 | 15.641 ± 0.030      | 2MASS       |                                  |
|             |           | 2451363.6290 | 13.270 ± 0.044      | 2MASS       |                                  |
|             |           | 2453892.9890 | 13.202 ± 0.030      | UKIDSS      | −0.010 ± 0.008                   |
|             |           | 2451363.6290 | 11.539 ± 0.035      | 2MASS       |                                  |
|             |           | 2453892.9949 | 11.408 ± 0.030      | UKIDSS      | −0.019 ± 0.007                   |
|             |           | 2455867.7927 | 11.353 ± 0.030      | UKIDSS      | −0.010 ± 0.008                   |
|             |           | 2457135.1454−2457510.2033 | 11.241−11.503  | OAWF        | −0.117 ± 0.026                   |
| OH 31.0−0.2 | K         | 2453536.0569 | 18.522 ± 0.384      | UKIDSS      |                                  |
| OH 37.1−0.8 | K         | 2453619.7938 | 16.483 ± 0.664      | UKIDSS      | −0.331 ± 0.063                   |
|             |           | 2455786.8148 | 15.882 ± 0.044      | UKIDSS      |                                  |
|             |           | 2453619.7938 | 15.528 ± 0.038      | UKIDSS      | −0.060 ± 0.010                   |
| OH 51.8−0.2 | K         | 2451076.6704 | 14.799 ± 0.131$^c$  | 2MASS       |                                  |
|             |           | 2453891.0838 | 14.938 ± 0.032      | UKIDSS      |                                  |
| OH 53.6−0.2 | J         | 2450606.8619 | 14.257 ± 0.029      | 2MASS       |                                  |
|             |           | 2453927.9395 | 14.199 ± 0.030      | UKIDSS      | −0.006 ± 0.005                   |
|             |           | 2450615.8619 | 12.985 ± 0.024      | 2MASS       |                                  |
|             |           | 2453927.9451 | 12.884 ± 0.030      | UKIDSS      | −0.011 ± 0.004                   |
|             |           | 2450615.8619 | 11.995 ± 0.021      | 2MASS       |                                  |
|             |           | 2453927.9503 | 11.821 ± 0.030      | UKIDSS      | −0.019 ± 0.004                   |
|             |           | 2455867.7852 | 11.771 ± 0.030      | UKIDSS      | −0.010 ± 0.008                   |
| OH 77.9+0.2 | J         | 2450985.9161 | 15.110 ± 0.042      | 2MASS       | −0.011 ± 0.006                   |
|             |           | 2454357.8615 | 15.006 ± 0.030      | UKIDSS      |                                  |
|             |           | 2450985.9161 | 15.110 ± 0.042      | 2MASS       |                                  |
|             |           | 2454357.8669 | 13.389 ± 0.030      | UKIDSS      | −0.020 ± 0.004                   |
|             |           | 2450985.9161 | 11.888 ± 0.017      | 2MASS       |                                  |
|             |           | 2454357.8709 | 11.719 ± 0.030      | UKIDSS      | −0.018 ± 0.004                   |
|             |           | 2455867.8329 | 11.662 ± 0.030      | UKIDSS      | −0.014 ± 0.011                   |
|             |           | 2457603.2533−2457986.1875 | 11.601−11.756  | OAWF        | −0.031 ± 0.026                   |

Notes.

$^a$ Magnitudes converted to WFCAM photometric system. The uncertainty of UKIDSS data is the SRSS of the 0.03 mag systematic uncertainty and the photometric error quoted from the UKIDSS-GPS catalog.

$^b$ For UKIDSS data, the rates are derived from the UKIDSS observation and the one before. For OAwF data, the rates are derived by linear fitting of the OAwF data.

$^c$ This magnitude is not converted to the WFCAM photometric system because it does not have the $(H - K)$$_{2MASS}$ required for system conversion.

selected as the reference star. This reference star is 9° north from OH 25.1−0.3 and has a K-band magnitude of ∼11.1 mag, which is close to the K-band magnitude of OH 25.1−0.3 (11.2−11.6 mag). The reference star for OH 77.9+0.2 is 2MASS J20282996+3907096, which exists 12° northwest from OH 77.9+0.2. The K-band magnitude (∼11.8 mag) is close to that of OH 77.9+0.2 (11.6−11.9 mag).

For OH 25.1−0.3, a slight periodic variability with an amplitude of ∼0.1 mag and a period of ∼50 days may be seen in the OAwF light curve. Even if we take into account this possible variability by setting the magnitude errors to be 0.2 mag, a linear fitting of all 2MASS, UKIDSS, and OAwF data gives a significant negative rate of change of −0.008 ± 0.003 mag yr$^{-1}$. Therefore, we conclude that OH 25.1−0.3 brightened since the 2MASS era even with the possible periodic variability. This brightening is also supported by the comparison of light curves of the target and the reference star, which shows that such a brightening is only seen in the target light curve. In the target light curve, only the data around MJD = 57,100−57,350 are relatively faint compared to the trend seen in the 2MASS and UKIDSS data, while the data around MJD = 56,000 seem to be on that trend. The discrepancy between the data around MJD = 57,100−57,350 and those around MJD = 56,000 is the cause of the large rate of change shown for the OAwF data in Table 2. If we assume that the faint magnitudes around MJD = 57,100−57,350 are caused by calibration problems and evaluate the rate of change since the second UKIDSS observation without these faint data, the rate of change is derived to be −0.021 ± 0.007 mag yr$^{-1}$. This is consistent with the values derived from 2MASS and UKIDSS observations.

As for OH 77.9+0.2, any periodic variability like OH 25.1−0.3 is not seen in the OAwF light curve. Although the overall magnitudes observed by OAwF are slightly fainter than those expected from the 2MASS–UKIDSS trend, the OAwF magnitudes are significantly brighter than the 2MASS magnitudes. Because the brightening trend is seen only in the target light curve, it can be concluded that OH 77.9+0.2 has also brightened since the 2MASS era. The rate of change derived from the OAwF light curve is consistent with those derived from the 2MASS and UKIDSS observations as in Table 2. Therefore, the magnitude offset between the 2MASS–UKIDSS trend and OAwF light curve may be caused by systematic error (see Appendix A.4).
As shown in Table 2, we have multicolor, multiepoch data for three objects, OH 25.1–0.3, OH 53.6–0.2, and OH 77.9+0.2, enabling us to study their color changes. Figure 7 shows the time variations of the \((H - K)\) and \((J - K)\) colors between the 2MASS and UKIDSS observations. The rates of the color change are summarized in Table 3. Conventionally, we have expected that a nonvariable OH/IR star becomes brighter and bluer as its mass-loss rate drops at the end of the AGB evolution. However, contrary to this picture, we have found that OH 25.1–0.3 and OH 77.9+0.2 do not show significant color change in both \((H - K)\) and \((J - K)\). On the other hand, the color of OH 53.6–0.2 in the UKIDSS observation is redder than that in the 2MASS data. The significance levels of the color changes are 1.4\(\sigma\) and 2.2\(\sigma\) in \((H - K)\) and \((J - K)\), respectively.

5. Origin of the Brightness Evolution

To investigate the origin of the observed long-term brightness evolution, we make a simple model based on the conventional picture and compare it with the observed rates of brightening and color change.

5.1. A Simple Model

In the conventional picture, it is thought that nonvariable OH/IR stars have ceased the dust supply to the circumstellar dust shell, and the dust shell is expected to expand its inner cavity. Therefore, we assume a spherical dust shell created by a stellar wind with a constant expansion velocity, \(v_{\text{exp}}\), and a constant dust mass-loss rate, \(\dot{M}_{d}\), and that its inner radius, \(r_{\text{in}}\), is increasing with time, \(t\), after the cessation of dust production.

At a wavelength \(\lambda\), the apparent magnitude of a star with an intrinsic apparent magnitude \(m_{\lambda,i}\) is written as

\[
m_{\lambda} = m_{\lambda,i} + A_{\lambda,c} + A_{\lambda,i},
\]

where \(A_{\lambda,c}\) and \(A_{\lambda,i}\) are the extinction caused by the circumstellar dust and interstellar dust, respectively. Here, we omit the thermal emission from the circumstellar dust shell, because it is difficult to model without mid- to far-infrared data simultaneously taken with the NIR data. This assumption is thought to be reasonable for a situation where enough time elapsed since the cessation of the dust supply and hot dust grains \((>700\ \text{K})\) disappeared (e.g., \(t \gtrsim 10\ \text{yr}\) for a star with \(L = 10^4\ \text{L}_{\odot}\) and \(v_{\text{exp}} = 10\ \text{km\ s}^{-1}\)). If such hot dust grains exist in the dust shell, their thermal emission can contribute to the NIR brightness especially at longer wavelengths. Such a possible contribution of the dust emission will be addressed in Section 5.4.

\(A_{\lambda,c}\) is described as

\[
A_{\lambda,c} = -2.5\log[\exp(-\sigma_{\lambda}N)] \approx 1.09\sigma_{\lambda} N,
\]

where \(\sigma_{\lambda}\) and \(N\) are the absorption cross-section and the column density of dust grains in the dust shell.

\(\dot{M}_{d}\) is related to the number density of dust grains, \(n_{d}\), as

\[
\dot{M}_{d} = 4\pi r^2 v_{\text{exp}} n_{d} N_{d},
\]

where \(r\) is the distance from the star, and \(m_{d}\) is the mass of a single dust particle. Because we assume a constant \(v_{\text{exp}}\) and a constant \(\dot{M}_{d}\), \(n_{d} r^2\) becomes a constant, \(C = \dot{M}_{d}(4\pi v_{\text{exp}} m_{d})^{-1}\).
Then, $N$ is written as

$$N = \int_{r_{\text{in}}}^{r_{\text{out}}} n_\lambda(r) \, dr = C \left( \frac{1}{r_{\text{in}}} - \frac{1}{r_{\text{out}}} \right),$$

where $r_{\text{in}}$ and $r_{\text{out}}$ are the inner and outer radii of the dust shell. If we assume that $r_{\text{out}}$ is sufficiently larger than $r_{\text{in}}$, $N$ is approximated to be

$$N \approx \frac{C}{r_{\text{in}}} = \frac{C}{r_{\text{in},0} + v_{\text{exp}} t},$$

where $r_{\text{in},0}$ is the inner radius of the dust shell at $t = 0$.

By substituting Equation (5) into Equation (2) and introducing a crossing-time parameter, $t_{\text{cross}} = r_{\text{in},0}/v_{\text{exp}}$, we get an expression of $A_{\lambda,c}$ as

$$A_{\lambda,c}(t) = \frac{A_{\lambda,c}(0)}{1 + t/t_{\text{cross}}}. \tag{6}$$

If we assume that the properties of the central star and interstellar extinction (i.e., $m_\lambda$ and $A_{\lambda,i}$) are constant, the rate of change of the apparent magnitude is described as

$$\frac{d m_\lambda}{d t}(t) = \frac{dA_{\lambda,c}}{d t} = -\frac{A_{\lambda,c}(0)}{t_{\text{cross}}(1 + t/t_{\text{cross}})^2}. \tag{7}$$

Another important observable is the rates of color change. In the model, the color in the wavelength range of $\lambda - \lambda'$ is

$$C_{\lambda'} = C_{\lambda',i} + E_{\lambda',c} + E_{\lambda',i}, \tag{8}$$

where $C_{\lambda',i}$ is the intrinsic color of the central star, $E_{\lambda',c}$ and $E_{\lambda',i}$ are the color excess in $\lambda - \lambda'$ caused by the circumstellar and interstellar dust, respectively. If we assume that the stellar properties and interstellar extinction (i.e., $C_{\lambda',i}$ and $E_{\lambda',i}$) are constant, the rate of color change is described by using Equations (2) and (8) as

$$\frac{dC_{\lambda'}}{d t}(t) = \left( \frac{\sigma_{\lambda}}{\sigma_{\lambda'}} - 1 \right) \frac{dA_{\lambda,c}}{d t}. \tag{9}$$

The wavelength dependence of the absorption cross-section is often expressed as a power-law function. If the power-law index is written as $p$ ($\sigma_{\lambda} \propto \lambda^{p}$), the rate of color change is written as

$$\frac{dC_{\lambda'}}{d t}(t) = \left[ \left( \frac{\lambda}{\lambda'} \right)^p - 1 \right] \frac{dA_{\lambda,c}}{d t}. \tag{10}$$

We compare the observed results with this model in the following sections.

### 5.2. K-band Brightening Rate

The $K$-band brightening rate can be calculated based on Equation (7) by substituting appropriate values of the crossing time and initial $K$-band circumstellar extinction, $A_{K,c}(0)$, to $t_{\text{cross}}$ and $A_{\lambda,c}(0)$, respectively.

According to the SED analysis by Justtanont & Tielens (1992), the inner radii of OH/IR stars are $1.3 - 15 \times 10^{12}$ m, and the expansion velocities are in the range of $2.3 - 24.2$ km s$^{-1}$. The combinations of these values lead to the crossing times of 2.8–24 yr. The actual expansion velocities of the six objects can be estimated from the velocity differences of the OH maser emission peaks. Based on the observations by Herman & Habing (1985), their expansion velocities are estimated to be $11.0 - 14.7$ km s$^{-1}$ and are actually in the parameter range above. The optical depth at $9.7 \mu$m, $\tau_{9.7}$, the peak of the silicate feature, is also given by Justtanont & Tielens (1992) and ranges from 0.03 to 19.6. The extinction in the $K$ band can be estimated from this $9.7 \mu$m optical depth to
be \( \lesssim 10 \) mag by assuming the silicate opacity proposed for OH/IR stars by Suh (1999).

If we assume \( A_{K,c}(0) = 10 \) mag as an example of the optically thickest dust shell of OH/IR stars and \( t_{cross} = 2.8 \)–24 yr, the time evolution of the \( K \)-band brightening rate is calculated as shown in Figure 8. In Figure 8, the thin solid and dashed lines show the calculated results. Based on Equation (7), the maximum value of the absolute brightening rate at each time \( t \) is found to be \( A_{K,c}(0)/4t \), which occurs in the model with \( t_{cross} = t \). This is shown with the thick solid line in Figure 8. The expected range is the region enclosed by these lines and indicated with the shaded region.

The \( K \)-band brightening rates observed between 2MASS and UKIDSS observations are shown with horizontal dotted lines in Figure 8. The \( K \)-band brightening rates are \( \lesssim 0.1 \) mag yr\(^{-1} \) except for OH 31.0–0.2. These values are found in \( t = 10\)–90 yr in the model. It means that their brightening rates can be explained as the dispersal effect of the dust shell at such times after the cessation of dust production. However, the large brightening rate of OH 31.0–0.2, \( 0.331 \pm 0.063 \) mag yr\(^{-1} \), is difficult to explain with this interpretation. Such a value is attained only at \( t \lesssim 8 \) yr as indicated by the thick line in Figure 8, which appears inconsistent given that this object was recognized as a nonvariable OH/IR star by Herman & Habing (1985), which is more than 10 yr earlier than 2MASS observations.

One possible cause of this large brightening rate is a large \( A_{K,c}(0) \) (i.e., very optically thick dust shell). As shown in Equation (7), the absolute value of the brightening rate is proportional to \( A_{K,c}(0) \). Therefore, a very optically thick dust shell with a large \( A_{K,c}(0) \) shows a large brightening rate in each elapsed time, and the time range showing a brightening rate can

### Table 3

| Object     | Color (H – K) | Rate of Change (mag yr\(^{-1} \)) |
|------------|---------------|-----------------------------------|
| OH 25.1–0.3 | +0.009 ± 0.010 |
| OH 53.6–0.2 | –0.002 ± 0.017 |
| OH 77.9+0.2 | –0.002 ± 0.017 |

Figure 7. Color change observed by 2MASS and UKIDSS. OH 25.1–0.3, OH 53.6–0.2, and OH 77.9+0.2 shown in the left, middle, and right panels, respectively. Top panels show \((H – K)\) variability, and bottom panels show \((J – K)\) variability. Horizontal axis shows the elapsed time from the first observation by 2MASS. Magnitudes are converted to the WFCAM system.

Figure 8. Comparison of \( K \)-band brightening rates between observation and model. The horizontal axis shows the elapsed time from the cessation of dust production. The thin solid and dashed curves show models with initial extinction \( A_{K,c}(0) = 10 \) mag and crossing time \( t_{cross} = 2.8 \) and 24 yr, respectively. The thick solid line shows the maximum rates under the assumption of \( A_{K,c}(0) = 10 \) mag. The shaded region shows the expected range in the model. \( K \)-band brightening rates observed between 2MASS and UKIDSS observations are shown with horizontal dotted lines.
be delayed. To obtain the elapsed time showing the large brightening rate of OH 31.0–0.2 (3–8 yr with \( A_{K,c}(0) = 10 \) mag) to \( \gtrsim 10 \) yr, we have to assume an extremely high \( A_{K,c}(0) \) of \( \gtrsim 20 \) mag. Such a high \( A_{K,c}(0) \) corresponds to a very large \( \tau_{0.7} \) of \( \gtrsim 40 \), and this scenario does not seem to be plausible. Therefore, the large brightening rate of OH 31.0–0.2 implies other mechanisms, rather than the dispersal of the dust shell.

5.3. Rate of Color Change

Based on Equations (7) and (10), we can calculate the rate of color change by additionally assuming the wavelength power-law index \( p \). The index \( p \) depends on the dust model, and various dust models are proposed for oxygen-rich AGB stars (Draine & Lee 1984; David & Papoular 1990; Ossenkopf et al. 1992; Suh 1999). They are well summarized in Figure 1 in the paper presented by Suh (1999). Their power-law indices in the NIR are \(-0.7 \) to \(-1.5 \), and if we assume \( p = -0.7 \), the rate of color change is calculated as shown with the solid and dashed lines in Figure 9.

Based on Figure 8, the elapsed time since the cessation of dust production for the three targets whose NIR colors were observed is 40–90 yr depending on the assumption of \( t_{\text{cross}} \). In this range, the NIR color becomes slightly bluer, according to Figure 9, as the dust shell continues to disperse. The expected rates of color change can be calculated from the observed \( K \)-band brightening rates based on Equation (10) independently from the assumption of \( A_{K,c}(0) \) and \( t_{\text{cross}} \). If we assume \( p = -0.7 \), the rates of change in the \((H-K)\) and \((J-K)\) colors for the three objects are calculated to be \(-0.0036\) to \(-0.0038\) and \(-0.0086\) to \(-0.0088\) mag yr\(^{-1}\), respectively. These values are shown by the gray regions in Figure 9. We can see that the observed values are greater than expected, indicating that these OH/IR stars did not become bluer as expected.

The difference between the observed and expected values of the rate of change in \((J-K)\) color corresponds to the difference of the observed \(J\)-band brightening rate and the \(K\)-band brightening rate scaled by \( (\lambda_J/\lambda_K)^p \), where \( \lambda_J \) and \( \lambda_K \) are the wavelengths of the \( J \) and \( K \) bands, respectively. Therefore, we evaluate the deviation of the rates of color change by calculating the significance of the difference between the \(J\)-band brightening rate and the scaled \(K\)-band brightening rate for \((H-K)\) color, use \( H \) instead of \( J \).

OH 25.1–0.3 shows a positive rate of change in \((H-K)\) color, which deviates from the expected value with 1.1\( \sigma \), while in \((J-K)\), it does not show a significant deviation. OH 77.9+0.2 shows a positive rate of \((J-K)\) color change which deviates from the expectation with 1.9\( \sigma \) significance, while it shows no significant deviation in the rate of \((H-K)\) color change. The rates of change of OH 53.6–0.2 are greater than the expected value with significances of 1.9\( \sigma \) and 2.9\( \sigma \) in the \((H-K)\) and \((J-K)\) colors, respectively. This means that OH 53.6–0.2 significantly became redder than expected.

Based on these results, nonvariable OH/IR stars do not seem to have become bluer as expected; some of them seem to have become redder even. At least, OH 53.6–0.2 clearly shows positive rates, and the observed reddening is difficult to explain with the dispersing dust shell model. These results depend on the assumption of \( p \). However, even if we decrease \( p \) to \(-1.5 \), to the end of the \( p \) range, the discrepancy between the observations and the model becomes more pronounced. Therefore, we need to consider other mechanisms rather than the dispersing of the circumstellar dust shell.

5.4. Possibilities beyond the Simple Model

We showed that the observed brightness evolution cannot be explained only with the dispersal of the dust shell and that there should be other mechanisms that were not considered in the simple model. We discuss such possibilities in the following sections.

5.4.1. Case of Warm Dust Shell

If the circumstellar dust shell is not yet dispersed, we would expect hot dust grains in the shell. In this case, their thermal emission contributes to the NIR brightness, especially in the \(K\) (and \(H\)) band. However, as the dust shell disperses, the dust temperature decreases, and the dust emission would decrease correspondingly. Therefore, the simple inclusion of dust emission in the simple model does not seem to explain the large brightening rate of OH 31.0–0.2. The color change of OH 53.6–0.2 is also difficult to explain. If the dust emission contributes to the NIR brightness, its contribution is larger at longer wavelengths, because the dust emission has a steep positive slope in the NIR. This contribution will decrease as the
dust temperature decreases. Then, the NIR color would become bluer. This is contrary to the observed change.

An increase of the stellar temperature and/or luminosity would heat the dust grains and increase the contribution of the dust emission to the NIR brightness. As a result, the $K$-band brightness can increase and the NIR color can become redder. These are qualitatively consistent with the observed changes in OH 31.0–0.2 and OH 53.6–0.2. If the increase in the stellar temperature and/or luminosity works more effectively than the dispersal effect of the dust shell, such a fast brightening and reddening phenomenon could occur.

5.4.2. Case of Cool Dust Shell

If the dust shell is dispersed to an extent where the dust becomes too cool to emit NIR emission, the NIR brightness is dominated by the attenuated stellar emission. In this case, one possibility to explain the fast brightening and reddening is a change of intrinsic stellar properties (i.e., luminosity increase and temperature decrease). Such a change may be caused by a fast stellar expansion as discussed in Section 5.5.

Another possibility is an emergence of dust thermal emission. As discussed above, the thermal emission from hot dust grains contribute more at longer wavelengths; its emergence could make the NIR emission brighter and redder. It can be realized by increasing hot dust grains. One possible way is to heat the dust grains by an increase of the stellar temperature and/or luminosity as discussed above. Another way is a new dust production, which produces hot dust grains around the central star. The emergence of hot dust grains by these effects could result in bright red emission in the NIR.

5.5. Relation with the Stellar Evolution

In the previous section, possible mechanisms for the fast brightening of OH 31.0–0.2 and the color change of OH 53.6–0.2 were proposed. We discuss them in the context of the stellar evolution.

The increase of stellar temperature—The increase of the stellar temperature is in line with the evolutionary scenario after the AGB phase. During the post-AGB phase, it is thought that the stellar temperature monotonically increases with time (Vassiliadis & Wood 1993, 1994; Blöcker 1995a, 1995b; Steffen et al. 1998; Miller Bertolami 2016). Although the definition of the end of the AGB phase remains ambiguous, various timescales are predicted for this transition. Miller Bertolami (2016) defines the end of the AGB phase as the time when the envelope mass equals 1% of the stellar mass. At this time, the stellar temperature is around 4000–5000 K (Miller Bertolami 2016), and the active pulsation and mass loss are expected to cease (Vassiliadis & Wood 1993, 1994; Blöcker 1995a, 1995b). Miller Bertolami (2016) predicts that the stellar temperature increases to ~7000 K on the order of 1–10 kyr after the end of the AGB, while Vassiliadis & Wood (1994) and Blöcker (1995b) predict longer and shorter timescales for the transition, respectively, depending on the particular mass-loss treatment adopted during this transition period. The shorter timescales tend to be predicted for stars with larger initial mass (Blöcker 1995b; Miller Bertolami 2016). Therefore, the observed fast brightening and color change may be related to such a fast temperature evolution of intermediate-mass stars. To validate this scenario, we need to reveal the spectral type of these stars.

The increase of stellar luminosity—The fast increase of the luminosity can occur in the thermal pulse cycles during the AGB phase. In the thermal pulse cycles, stellar properties vary with time. Their temporal variations are theoretically calculated in some cases, and in the early phase of a thermal pulse cycle, fast time variations of the stellar properties are expected to occur (Vassiliadis & Wood 1993; Blöcker 1995a; Steffen et al. 1998; Molnár et al. 2019). A detailed calculation in the early phase of a thermal pulse cycle is given by Molnár et al. (2019). Their model shows that the star rapidly shrinks to half of its radius in a few hundred years and then rapidly expands to greater than the original size in the next few hundred years. Such a fast variation is also seen in the model calculated by Steffen et al. (1998). The fast expansion can cause a fast increase of the stellar luminosity by a factor of >2 (Vassiliadis & Wood 1993; Blöcker 1995a; Steffen et al. 1998). This kind of luminosity increase can contribute to the fast brightening and color change by heating dust grains. To quantitatively investigate this possibility, longer-wavelength infrared observations and detailed radiative-transfer modeling are needed.

If this scenario is true, the central star must be in the AGB phase, and the nonvariable state must occur in the thermal pulse cycles. Trabucchi et al. (2019) report that the dominant pulsation mode can be switched from the fundamental mode (i.e., Mira-like large-amplitude pulsation) to the first-overtone mode (i.e., relatively small-amplitude pulsation) after such a fast shrinking, especially in the late AGB phase of low-mass stars. The nonvariability may be caused by such a pulsation-mode switching.

The decrease of stellar temperature—The decrease of stellar temperature is also expected to occur together with the luminosity increase in the fast stellar expansion in the thermal pulse cycles. In the model calculated by Steffen et al. (1998), a temperature decrease of a few hundred Kelvin in a few hundred years is predicted. If such a temperature decrease occurs when the dust emission is negligible, it will cause the reddening in the NIR. However, the color change of OH 53.6–0.2 requires a 10 times faster decrease of the stellar temperature. Therefore, this scenario does not seem to be plausible. Nevertheless, it should be investigated with evolutionary calculations with a wide range of parameters.

New dust production—New dust production is not expected after the end of the AGB. However, if the nonvariable OH/IR stars are still on the AGB phase, fast dust production can occur after a temporal reduction of dust production in the thermal pulse cycles.

Steffen et al. (1998) also calculated the time evolution of the mass-loss rate and SED in the late stage of the AGB phase. In their model, the mass-loss rate decreases with the fast shrinkage of the central star, and then suddenly increases with the stellar expansion. The enhancement of the stellar mass loss produces hot dust grains and cause the emergence of NIR dust emission. As a result, the $K$-band brightness and NIR color suddenly increase. Although the $K$-band brightening rate and the rate of $(J - K)$ color change in their model are smaller than the observed values by a factor of 3–4, this behavior is qualitatively consistent with the observed result. If such models with different parameters are investigated, the model that quantitatively matches the observation may be found.
5.6. Future Investigations

We have demonstrated that the observed K-band brightening was generally consistent with the conventional view of nonvariable OH/IR stars. However, we have also found it difficult to explain the large brightening rate of OH 31.0−0.2 and the reddening of OH 53.6−0.2. To reveal the mechanism of the observed phenomena and understand the currently veiled evolution from the AGB phase to the post-AGB phase, multiwavelength monitoring, spectroscopy, and distance measurements are needed.

Monitoring observations would segregate the long-term variabilities from possible small-amplitude variability as seen in OH 25.1−0.2. Multiwavelength observations are also important. We must observationally establish the NIR color evolution of the nonvariable OH/IR stars that exhibit long-term brightening to determine whether or not the conventional view would still be valid.

Stellar properties such as spectral type and luminosity are also important especially to reveal the evolutionary states of nonvariable OH/IR stars. However, the spectral type of most nonvariable OH/IR stars is largely unknown. We need spectroscopic observations with high sensitivity and high spatial resolution to reveal the spectral type of the objects that are faint in the short-wavelength range and are in the crowded galactic plane.

The luminosity is also relatively unknown because their distances are uncertain. We do not find reliable distances to these 16 nonvariable OH/IR stars even in Gaia DR2 (Gaia Collaboration et al. 2018). The phase-lag method is a useful way to measure the distance to OH/IR stars. In this method, it is required to measure the phase difference of the variabilities of the two OH maser emission peaks. However, the nonvariable OH/IR stars do not show significant variability of OH maser emission, and this method is not applicable for these objects (van Langevelde et al. 1990). In these circumstances, parallax measurements using maser observations with Very Large Baseline Interferometry is a good way to determine the distance more accurately (e.g., Nakagawa et al. 2019).

Model calculations are also important. The observables derived by combining stellar-evolution models, hydrodynamic stellar-wind models, and radiative-transfer calculations are very useful to interpret the observational results (e.g., Steffen et al. 1998). Recently, advanced stellar-evolution models (e.g., Miller Bertolami 2016) and hydrodynamic stellar-wind models (e.g., Bladh et al. 2019) have been developed. The studies on the observables incorporating the recent models will be highly useful to interpret the future observations and possibly resolve the origin of the brightness evolution of nonvariable OH/IR stars. At the same time, these numerical models can reproduce the observed behaviors of nonvariable OH/IR stars.

6. Summary

We investigated the long-term brightness evolution of 16 nonvariable OH/IR stars (Herman & Habing 1985). Based on the infrared images taken with 2MASS and SST/IRAC, their precise positions on the sky were determined. Their recent NIR magnitudes were looked up in the UKIDSS-GPS and OAOWFPC data. As a result, multiepoch data were established for seven objects. However, for one object (OH 51.8−0.2), we were unable to determine the time evolution of its brightness.

All of the remaining six objects appeared to have brightened in a few thousand days. Their K-band brightening rate ranges from 0.010 to 0.331 mag yr$^{-1}$. The observed K-band brightening is basically explained with a simple model of a dispersing dust shell with typical parameters of OH/IR stars. However, the largest brightening rate, 0.331 mag yr$^{-1}$, is difficult to explain with this model. This large brightening rate implies the presence of other mechanisms.

For three of the six objects, OH 25.1−0.3, OH 53.6−0.2, and OH 77.9+0.2, we examined the long-term brightness evolution for more than one band. None of these three objects appeared to have become bluer, and among the three objects, OH 53.6−0.2 was significantly confirmed to have been reddened. This color change is contrary to the expectation from the dispersal of the dust shell and requires to consider other mechanisms.

An increase of the dust emission could explain both observed phenomena simultaneously. One possible mechanism is an increase of the stellar temperature, which is expected to occur in the transition from the AGB phase to the post-AGB phase. Another possibility is an increase of the stellar luminosity or new dust production which can happen with the fast stellar expansion in the thermal pulse cycles during the AGB phase. To explain the observed reddening, a reduction of the stellar temperature was also proposed.

To understand the cause of the observed variabilities, further investigations in theoretical calculations and observations are needed. Such studies will lead to a better understanding of the evolutionary states of nonvariable OH/IR stars and the evolution of AGB stars.

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Facilities: IRSA, Spitzer, CTIO:2MASS, FLWO:2MASS, UKIRT, OAO:0.91 m.
Software: SExtractor (Bertin & Arnouts 1996), IRSA, IRSA viewer, SIMBAD (Wenger et al. 2000), VizieR, CDS X-match.

Appendix

Systematic Errors

To further validate the time evolution of the NIR magnitudes of several OH/IR stars found in Section 4, we examine the systematic errors in the various methods of photometry employed and residual calibration errors.

A.1. 2MASS Data

2MASS magnitudes are available for OH 25.1−0.3, OH 53.6−0.2, and OH 77.9+0.2. They are summarized in Table A1 with the relevant flags. The [jbk] m is the default magnitude used in the 2MASS catalog. The rd_flg shows the measurement method used in deriving the [jbk] m magnitude. The rd_flg of
these data is always 2, which means that the \([jhk]_m\) magnitudes are derived by profile-fitting measurements (Cutri et al. 2006; Skrutskie et al. 2006). The profile fitting is performed to fit the pixel values in a circle with a radius of 2 pixels (2″) centered on the detected source with multiple point-spread functions (PSFs). The 2MASS PSC also gives magnitudes measured with aperture photometry, \([jhk]_m\_stap\), which are curve-of-growth-corrected magnitudes measured with a 4″ radius aperture. We compare these two magnitudes to assess the systematic errors and missing flux.

Both of the \([jhk]_m\) and \([jhk]_m\_stap\) magnitudes of OH 53.6–0.2 and OH 77.9–0.2 in all bands are consistent with each other within the corresponding uncertainty. The \(K_S\)-band magnitudes of OH 25.1–0.3 are also consistent with each other. This means that these \([jhk]_m\) are good values of the object brightness without any significant amount of missing fluxes.

The \([jhk]_m\_stap\) magnitudes of OH 25.1–0.3 in the \(J\) and \(H\) bands are found to be brighter than the \([jhk]_m\) magnitudes by 0.7199 and 0.0606 mag with significances of \(\sim5.1\sigma\) and \(\sim1.2\sigma\), respectively. As shown in Figure 1, as the region around OH 25.1–0.3 is crowded, emission from surrounding stars can contaminate the source magnitude measured with the 4″ radius aperture. Therefore, the difference between the \([jhk]_m\) and \([jhk]_m\_stap\) magnitudes is likely caused by the contamination, and the \([jhk]_m\) magnitudes are thought to be appropriate for the brightness of the object.

The reduced chi-squared value and the number of required sources of the profile fitting are referred to as \([jhk]_\text{psfchi}\) and bl_flg, respectively. Except for the \(J\)-band data of OH 25.1–0.3, \([jhk]_\text{psfchi}\) is \(\leq2\) and bl_flg is 1. This means that the sources are well fitted with one PSF, and it is consistent with the result that the \([jhk]_m\) magnitudes do not have any significant amount of missing flux. As for the \(J\)-band data of OH 25.1–0.3, bl_flg is 2. This suggests that some extended component can contribute to the source brightness, and this may be related to the large difference between the \([jhk]_m\) and \([jhk]_m\_stap\) magnitudes.

Table A1 also shows that some data have a nonzero cc_flg, indicating possible contamination or confusion. OH 77.9+0.2 shows an s flag in the \(J\) and \(H\) bands. This indicates possible contamination caused by stripe patterns around bright stars. In the case of OH 77.9+0.2, a bright star is found 2″ north from the target. We confirm that stripe patterns caused by the bright star are not apparent in the 2MASS images at the target position and concluded that the \(J\)- and \(H\)-band magnitudes are reliable enough. OH 25.1–0.3 has a p flag in the \(J\)-band data. It indicates possible contamination caused by a persistence pattern caused by bright stars. We cannot find such a pattern clearly in the 2MASS image, but it is difficult to find it in the crowded region around OH 25.1–0.3. Therefore, the \(J\)-band magnitude may not be as reliable.

Based on these assessments, we conclude that all 2MASS data except for the \(J\)-band data of OH 25.1–0.3 are reliable. If we rely only on the \(H\)- and \(K\)-band magnitudes, OH 25.1–0.3 is thought to become red as observed for OH 53.6–0.2.

A.2. UKIDSS Data

The UKIDSS magnitudes are measured based on the aperture photometry with various aperture radii. The aperture-photometry-based magnitudes are given as AperMag[1–13] measured with aperture diameters of 1″, \(\sqrt{2}\)″, 2″, 2\(\sqrt{2}\)″, 4″, 4\(\sqrt{2}\)″, 8″... (Irwin et al. 2004; Lucas et al. 2008). The default magnitude, AperMag3, is measured with a 2″ diameter aperture. To check the validity of AperMag3, we examine the aperture-diameter dependence of the measured magnitudes.

Figure A1 shows the aperture-size dependence of the measured magnitudes. A smaller aperture setting can give more reliable magnitudes of sources in crowded regions. However, if the source has a radial profile thicker than a PSF because of some causes such as seeing and intrinsic diffuse emissions, a small aperture setting can result in underestimating the source brightness. In such a case, the aperture-size dependence will show an increasing trend. On the other hand, a large aperture setting can lead to unstable measurement of the source brightness, because it is easily affected by contamination from surrounding stars and the poorly estimated sky background. Therefore, reliable magnitudes are thought to be in between these two cases, and such a region will appear as a plateau region in Figure A1.

In the case of OH 25.1–0.3, the default magnitude is on the plateau in all bands and seems to be reliable as the source brightness. However, for OH 53.6–0.2 and OH 77.9+0.2, the default magnitude is not on the plateau, and the magnitudes measured with larger apertures may be better for the total source brightness. If we employ the magnitudes measured with larger apertures, the source brightness increases by 0.1–0.3 mag, and the brightness since the 2MASS era will be more significant. In the case of OH 15.7+0.8, the default

### Table A1

**Detailed List of 2MASS Data Used for OH 25.1–0.3, OH 53.6–0.2, and OH 77.9+0.2**

| Object   | Band | \([jhk]_m\) (mag) | \([jhk]_\text{msigcom}\) (mag) | ph_qual | \(\text{rd}_\text{flg}\) | \(\text{bl}_\text{flg}\) | \(\text{cc}_\text{flg}\) | \([jhk]_\text{psfchi}\) | \([jhk]_m\_stap\) (mag) | \([jhk]_\text{msigstdap}\) (mag) |
|----------|------|------------------|-------------------------------|---------|----------------|----------------|----------------|----------------|----------------|----------------|
| OH 25.1–0.3 | \(J\) | 15.852           | 0.107                         | B       | 2              | 2              | p              | 1.31            | 15.133         | 0.092           |
|          | \(H\) | 13.121           | 0.044                         | A       | 2              | 1              | 0              | 1.91            | 13.061         | 0.026           |
|          | \(K_S\) | 11.528          | 0.035                         | A       | 2              | 1              | 0              | 2.38            | 11.511         | 0.017           |
| OH 53.6–0.2 | \(J\) | 14.332           | 0.029                         | A       | 2              | 1              | 0              | 1.28            | 14.313         | 0.025           |
|          | \(H\) | 12.912           | 0.024                         | A       | 2              | 1              | 0              | 0.97            | 12.893         | 0.030           |
|          | \(K_S\) | 11.965          | 0.021                         | A       | 2              | 1              | 0              | 1.10            | 11.960         | 0.027           |
| OH 77.9+0.2 | \(J\) | 15.196           | 0.042                         | A       | 2              | 1              | s              | 1.04            | 15.183         | 0.051           |
|          | \(H\) | 13.463           | 0.027                         | A       | 2              | 1              | s              | 1.58            | 13.479         | 0.049           |
|          | \(K_S\) | 11.877          | 0.017                         | A       | 2              | 1              | 0              | 1.43            | 11.895         | 0.022           |

**Note.**

* Magnitudes in the 2MASS system.
The magnitude for the first UKIDSS observation is on the plateau. As for the second observation, the magnitudes measured with apertures larger than the default are unstable. Therefore, the default magnitude seems to be good as the source magnitude. OH 31.0−0.2 shows decreasing trends with increasing aperture diameter in both data, and magnitudes measured with smaller apertures seem to be reliable. If we use the magnitudes measured with aperture diameters of 1″ and √2″, the source will get brighter by 0.6−0.7 and 0.06−0.07 mag in the first and second data, respectively. In the case of OH 37.1−0.8, the default magnitude is at the plateau in the second data, but in the first data, it is at the edge of the plateau. The magnitudes measured with aperture diameters larger than 4″ are unstable. Therefore, the magnitude measured with an aperture diameter of 2√2″ seems to be most reliable, but it is consistent with the default magnitude within the error.

The magnitude differences between two UKIDSS K-band observations are almost independent of the aperture settings. However, as for the case of OH 31.0−0.2, the magnitude difference between the two UKIDSS observations may be overestimated when using the default magnitudes. If we employ the magnitudes measured with smaller apertures, the magnitude difference between the two UKIDSS observations decreases by ~0.6 mag, but the difference (brightening) is still significant. This correction also decreases the brightening rate of OH 31.0−0.2 to 0.23 mag yr⁻¹. This value still requires a short elapsed time of ≲11 yr since the cessation of dust production, which is difficult to explain with the dispersal of dust.
the dust shell as discussed in Section 5.2. Therefore, this correction does not change the conclusion that OH 31.0−0.2 is showing a very fast brightening, which cannot be explained with the dispersal of the dust shell.

The magnitude differences between two UKIDSS K-band observations of the surrounding objects are shown in Figure A2 to examine the systematic errors between the magnitude difference and object brightness. To examine the local systematic errors, we select objects within 3′ from the target OH/IR stars and compute the average and standard deviation of the magnitude difference for each 1 mag bin (Figure A2). The data for the nonvariable OH/IR stars are also shown by black diamonds, and we find that the observed magnitude differences of our targets significantly deviate from the average. Therefore, we conclude that the brightening observed between two UKIDSS observations is real even if the systematic errors are considered.

A.3. 2MASS–UKIDSS Difference

The systematic difference between the 2MASS and WFCAM systems is corrected by the system conversion as described in Section 3. However, there can be a residual systematic difference that cannot be corrected with the system conversion. To assess such a residual systematic error, we examine the magnitude differences between the 2MASS and UKIDSS observations.

Figures A3 and A4 show the magnitude difference plotted against 2MASS magnitudes and 2MASS colors, respectively. Gray dots represent the data corresponding to objects within 3′ from the target. To reduce the degree of data scatter, data with 2MASS photometric errors of >0.2 mag are removed. In Figure A4, only bright objects are plotted: the magnitude threshold is set to 14, 15, and 15 mag for OH 25.1−0.3, OH 53.6−0.2, and OH 77.9+0.2, respectively. The difference is calculated after converting the 2MASS magnitudes to the WFCAM photometric system. The average and standard deviation are calculated in each 1 mag bin in the horizontal direction, and the 1σ, 2σ, and 3σ regions are indicated by the solid, dotted, and dashed–dotted lines in each panel. In the K-band plot for OH 77.9+0.2 in Figure A4, the average and standard deviation of the magnitude difference are calculated in a 2 mag color bin because of the small number of samples.

For OH 25.1−0.3, systematic trends with a positive slope are seen in all bands in Figure A3. The magnitude difference in the K band slightly deviates from the systematic trend, while those in the J and H bands are not significant. The average magnitude differences in the bins containing the target are $-0.039$, $-0.043$, and 0.028 mag in the J, H, and K bands, respectively. These are within the systematic calibration error expected from the systematic uncertainties of 2MASS and UKIDSS observations. The color dependence of the magnitude difference is not significant. If we correct the measured systematic errors, the brightening in the J and H bands becomes insignificant, while that in the K band increases by $\sim20\%$. The color changes also get more significant.

In the plots for OH 53.6−0.2, the data show flat patterns in the range around the target position in both Figures A3 and A4. OH 53.6−0.2 shows deviation from the trend in all bands, especially in the K band. The absolute values of the mean magnitude differences in the bins where the target is contained are 0.004−0.039 and are in the range expected from calibration errors. Because this kind of error is already taken into account, we do not need extra correction for these offsets.

Figure A2. Magnitude differences between two UKIDSS observations plotted against the observed magnitude in the K band. $k_1$ and $k_2$ show the K-band magnitude observed in the first and second UKIDSS observations, respectively. Gray dots show the objects within 3′ around each target. The solid, dotted, and dashed–dotted lines show the 1σ, 2σ, and 3σ regions from the average calculated in 1 mag bins. The data of the target are shown by the black diamonds in each panel. The error bars show the photometric uncertainties without systematic errors.
The plots for OH 77.9+0.2 also show flat patterns around the target position in both Figures A3 and A4, and the data of OH 77.9+0.2 significantly deviate from the trends seen in the surrounding stars. However, in Figure A3, faint stars show slightly large offsets in the $J$ band. In the bin containing the target, the average magnitude difference is 0.072 mag in the $J$ band. This is a large value to explain with the systematic uncertainties of the 2MASS and UKIDSS observations, while other bands show only small differences. By correcting the large offset in the $J$ band, the brightening of OH 77.9+0.2 in the $J$ band increases by a factor of 1.7, and the rate of change in the $(J-K)$ color changes to $-0.001 \pm 0.007$ mag yr$^{-1}$. Even if this correction is applied, the result that OH 77.9+0.2 does not show a significant color change is not affected.

Based on the discussion above, the findings of this work, the $K$-band brightening and the absence of the expected bluing, are not affected by the possible residual systematic errors.

### A.4. OAOWFC Data

To assess the systematic errors of the OAOWFC data, we examine the light curve of the reference stars in detail. Figure A5 shows the close-up plots of the light curves. The dashed lines are the average magnitudes calculated from the 2MASS and UKIDSS observations. The standard deviations of the OAOWFC data are 2%–3% and consistent with the measurement errors shown with the error bars in the bottom panels of Figure A5. It means that the photometric measurements and error evaluation of the OAOWFC data are properly performed.

The 2MASS and UKIDSS data are distributed within $\pm 3$–4% around the average magnitudes. This is reasonable based on the systematic uncertainties of 2MASS and UKIDSS data of 2%–3%. The typical deviations of the OAOWFC data from the average magnitudes are $\sim 3$% as seen in Figure A5. In addition, the OAOWFC data seem to show slightly fainter magnitudes.

![Figure A3](https://example.com/figureA3.png)

**Figure A3.** Residual systematic magnitude difference between 2MASS and UKIDSS observations plotted against 2MASS magnitudes. Object name and observation band are shown in the upper-left corner of each panel. In the derivation of the magnitude difference, 2MASS magnitudes are converted to the WFCAM photometric system. The average and standard deviation of the magnitude difference are calculated in each 1 mag bin in the horizontal direction. The solid, dotted, and dashed-dotted lines show the 1σ, 2σ, and 3σ regions from the average values. The targets are shown with black circles, and the error bars show only photometric uncertainties.
than the average. This tendency can be the reason for the magnitude difference between the OAOWFC observations and the 2MASS–UKIDSS trend seen in Figure 6. We do not further investigate the cause of this systematic error because it is out of the scope of this study, but if we correct this systematic error, the brightening of the target objects becomes more significant.

Finally, the light curve of the reference star for OH 25.1−0.3 does not show periodic variabilities unlike OH 25.1−0.3. This means that the periodic variability seen in the light curve of OH 25.1−0.3 can be a real variability. Because the number of observations is small, continuous and dense monitoring observations are required to validate the variability.

Figure A4. Same as Figure A3, but plotted against 2MASS colors. The average and standard deviation in the K-band plot for OH 77.9+0.2 (bottom-right panel) are calculated in 2 mag color bin.
Figure A5. K-band light curves of reference stars. The left and right panels show the light curves of the reference stars for OH 25.1−0.3 and OH 77.9+0.2, respectively. The bottom panels are magnified plots of the OAOWFC data. The magnified regions are shown with squared regions in the top panels. Dashed lines show the mean magnitude derived from 2MASS and UKIDSS observations. All of the magnitudes are converted to the WFCAM system.

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