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PROPERTIES OF THE VARIATION OF THE INFRARED EMISSION OF OH/IR STARS II. THE L BAND LIGHT CURVES

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ABSTRACT

In order to study properties of the pulsation in the infrared emission for long period variables, we collect and analyze the infrared observational data at L band for 12 OH/IR. The observation data cover about three decades including recent data from the *ISO* and *Spitzer*. We use the Marquardt-Levenberg algorithm to determine the pulsation period and amplitude for each star and compare them with results of previous investigations at infrared and radio bands. We obtain the relationship between the pulsation periods and the amplitudes at L band. Contrary to the results at K band, there is no difference of the trends in the short and long period regions of the period-luminosity relation at L band. This may be due to the molecular absorption effect at K band. The correlations among the L band parameters, IRAS [12-25] colors, and K band parameters may be explained as results of the dust shell parameters affected by the stellar pulsation. The large scatter of the correlation could be due to the existence of a distribution of central stars with various masses and pulsation modes.

Key words : stars — AGB and post-AGB — infrared: stars — stars: oscillations — circumstellar matter — dust — extinction

1. INTRODUCTION

OH/IR stars are believed to be the final phase of an oxygen-rich asymptotic giant branch (AGB) star showing OH maser emission at 1612 MHz. These stars are generally Mira type variables characterized by the long period and large amplitude pulsation. Shock waves caused by the strong pulsation and radiation pressure on the dust grains drive dusty stellar winds with high mass-loss rates (10^{-8} - $10^{-4} M_{\odot}/yr$). The central stars have optically thick dust envelopes.

The central stars have a rather wide range of masses and pulsate with various pulsation modes (Barthès & Luri 2001). It is known that the pulsating central star can affect not only the overall luminosity but also the shape of the spectral energy distribution (SED). This means that the overall properties of the dust shell vary with the phase of pulsation. Le Bertre (1988) modeled the dust shell at different phase of a carbon-rich AGB star (R For). Suh (2002) discussed a mechanism for crystallization of dust grains through the pulsation. Suh (2004) proposed three possible dust models to explain the SED changes for O-rich AGB stars. The study of the precise pulsation mechanisms may provide the clues to understand the fundamental quantities (mass, luminosity, radius etc.) of the central stars.

Spitzer space telescope (*Spitzer*), lunched in 2003, has the Infrared Array Camera (IRAC) designed for observations of faint sources and deep large-area surveys (Fazio et al. 2004). The IRAC has four channels that can obtain the broadband images with high sensitivity at 3.6, 4.5, 5.8, and 8.0 μm simultaneously. The IRAC data at 3.55 μm would be useful to improve L band light curves.

Suh & Kwon 2009a (hereafter paper I) investigated the K band light curves for 9 OH/IR stars. In this paper, we present the light curves at L band for selected 12 OH/IR stars including the 9 stars from paper I.

Table 1.
The sample stars

OH name	IRAS	R.A.(J2000) h:m:s	Dec.(J2000) d:m:s	Ref.
26.2−0.6	18385−0617	18 41 14.3	−06 15 00.6	S
26.4−1.9	18437−0643	18 46 26.8	−06 40 34.1	S
26.5+0.6	18348−0526	18 37 32.5	−05 23 59.7	S
28.7−0.6	18431−0403	18 45 48.4	−04 00 46.8	S
30.1−0.2	18445−0238	18 47 09.8	−02 35 36.2	S
30.7+0.4	18432−0149	18 45 52.4	−01 46 42.8	S
32.8−0.3	18498−0017	18 52 22.2	−00 14 11.0	E
39.9+0.0	19017+0608	19 04 09.7	+06 13 15.9	S
42.3−0.1	19067+0811	19 09 08.3	+08 16 33.7	S
45.5+0.1	-	19 14 19.6	+11 10 35.0	E
127.8+0.0	01304+6211	01 33 51.2	+62 26 53.0	E
178.0−31.4 (IK Tau)	03507+1115	03 53 28.8	+11 24 22.6	L

S=Sevenster et al. 2001; E=Engels & Jiménez-Esteban 2007; L= Loup et al.1993.

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Table 2.
The L band observations for the sample stars

Reference	26.2-0.6	26.4-1.9	26.5+0.6	28.7-0.6	30.1-0.2	30.7+0.4
Schultz et al. (1976)	1	1(1)	1	1	.	1
Lebofsky et al. (1978)	.	.	1	.	.	.
Evans & Beckwith (1977)	.	.	3	.	3	.
Ney & Merrill (1980)	.	.	10	.	.	.
Werner et al. (1980)	.	.	1	.	1	.
Engels (1982)	11	11(1)	11(1)	10	11	11
Willems & de Jong (1982)	.	2	2	.	.	.
Grasdalen et al. (1983)	.	.	1	.	.	.
Fix & Mutel (1984)	.	1	.	.	.	.
Herman et al. (1984)	1	1	.	1	1	1
Gehrz et al. (1985)	3	4	.	3	.	5
Jones et al. (1990)	.	.	11(2)	.	.	.
Nyman et al. (1993)	1	1	1	1	1	1
Le Bertre (1993)	.	.	15	.	.	.
Lepine et al. (1995)	.	.	1	.	.	.
Olivier et al. (2001)	.	.	16	.	.	.
Justtanont et al. (2006)	.	.	1(1)	.	.	1(1)
ISO	1	.	2	.	.	.
Spitzer	1	1	(1*)	(1*)	(1*)	(1*)
total number	19	22(2)	78(5)	17(1)	18(1)	21(2)

Reference	32.8-0.3	39.9+0.0	42.3-0.1	45.5+0.1	127.8+0.0	IK Tau
Strecker & Ney (1974)	.	.	.	.	.	3
Lebofsky et al. (1976)	.	.	.	.	1	.
Schultz et al. (1976)	1	.	.	1	.	.
Evans & Beckwith (1977)	2	.	.	4	.	.
Ney & Merrill (1980)	.	.	.	2	1	15(1)
Werner et al. (1980)	1	.	.	1	.	.
Engels (1982)	11	10	7	10	.	.
Grasdalen et al. (1983)	.	.	.	.	2	.
Fix & Mutel (1984)	.	.	1	.	.	.
Herman et al. (1984)	1	1	1	.	.	.
Gehrz et al. (1985)	.	3	2(1)	1	3	.
Persi et al. (1990)	.	.	.	.	2	.
Jones et al. (1990)	.	.	.	.	10	10
Fouque et al. (1992)	.	.	.	.	.	1
Noguchi (1993)	.	.	.	.	1	.
Nyman et al. (1993)	1	1(1)	1	1	.	.
Le Bertre (1993)	.	.	.	.	.	15
Olivier et al. (2001)	.	.	.	.	.	105(1)
Justtanont et al. (2006)	1	1	1	.	.	.
ISO	1	.	.	.	2	.
Spitzer	1	1(1)	2	1(1)	.	.
total number	20	17(2)	15(1)	21(1)	22	149(2)

$*$: saturated (see text)

We analyze the light curves to find relevant pulsation parameters and discuss the physical meaning.

2. SAMPLE STARS

In this paper, we choose 12 OH/IR stars having a wide range of pulsation periods. The sample stars are listed in Table 1 with the IRAS PSC number, the radio position and the references for the position. We include 3 more stars (OH 32.8-0.3, OH 42.3-0.1 and IK Tau) compared to paper I. The pulsation periods of the sample stars range between 300 days and 2000 days.

Infrared Space Observatory (*ISO*) provides us with useful data for light curves. We use flux density at 3.6 μm of the Short Wavelength Spectrometer (SWS) with the wide wavelength coverage ($\lambda = 2.4 - 45.2 \mu$m) and ISOPHOT (PHT). PHT has two different detectors; PHT-P and PHT-S. PHT-S has two low-resolution grating spectrometers that cover the wavelength ranges 2.5-4.9 μm (PHT-SS) and 5.8-11.6 μm (PHT-SL). In this work, We use the PHT-SS data at 3.6 μm.

In Table 2, we list the number of data used for this paper. We use the original data without further reduction although the exact wavelengths for each bandpass used by many authors are slightly different. We consider that the difference would not make major errors. The numbers of unused data for the analysis to determine the pulsation parameters are marked by parenthesis (see Section 3).

Compared with previous investigations, we use much

Table 3.
Photometry of *Spitzer* observations

Name	Obs. time y-m-d	Flux [mJy]	Note
26.2−0.6	2004 04 21	2570	G
26.4−1.9	2007-05-11	5180	G
26.5+0.6	2004-04-21	6550	S
28.7−0.6	2004-04-22	2960	S
30.1−0.2	2004-04-22	2210	S
30.7+0.4	2004-04-22	1910	S
32.8−0.3	2004-04-22	4940	G
39.9+0.0	2004-10-09	1300	G†
42.3−0.1	2003-10-02	194	
42.3−0.1	2004-10-09	619	
45.5+0.1	2004-10-10	2150	G†

†: lower limit (see text)

larger database because of the recent *ISO*, *Spitzer*, and ground-based observations. The range of time for the database is about 30 years and the data points are increased more than 50 percent from the investigation of Engels (1982). For OH 26.5+0.6, the data is about 6 times larger than that used by Engels (1982). Because of the larger data base, the new pulsation parameters would show much smaller errors.

To obtain the standard flux in W/m^2 for all the data, we use the zero-magnitude calibrating methods. The zero-magnitude calibrating data are taken from the related references.

2.1 The *Spitzer* Data

The Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE, Benjamin et al. 2003), a *Spitzer* Legacy Science Program, surveyed a span of 130 degrees in longitude and 2-4 degrees in latitude of our galactic plan with the IRAC on the *Spitzer*. As the IRAC 3.55 μm band share similarity with the standard *L* band, we use the data for our analysis.

All the sample stars except IK Tau and OH 127.8+0.0 were observed by the GLIMPSE survey and OH 42.3-0.1 was observed twice. We use the Basic Calibrated Data (BCD) for photometry. Bright sources in the IRAC make electronic artifacts such as saturation, muxbleed, and column pull-down. The sensitivity of IRAC is too high to observe one of the brightest objects in the infrared sky. Therefore, the bright OH/IR stars are saturated easily.

Only one star (OH 42.3-0.1), the faintest stars at *L* band among the sample stars, is not saturated. The fluxes of OH 42.3-0.1 are extracted using the aperture photometry package in IRAF. All the other sources show very low flux density level caused by saturation. According to GLIMPSE3D v1.0 Data Release Document*, the saturation limit for GLIMPSE is 7 mag at 3.55 micron band. Although OH 42.3-0.1 is slightly brighter than this limit, the photometry is usable. The photometry of this star falls in the error range of the photometry using point spread function (PSF) of GLIMPSE (see below).

The photometry of some softly saturated stars can be extracted in the wing regions.* The flux density can be obtained if the source is within a circle of a radius of 24-pixel (the PSF-shape region) surrounding a saturated source (GLIMPSE3D). We use the corrected flux density of the softly saturated sources (5 sources) from the three GLIMPSE source catalogs at NASA/IPAC Infrared Science Archive (IRSA) web site.† But this method can not resolve all the saturation problems. We find that more heavily saturated sources (OH 39.9+0.0 and OH 45.5+0.1) show much lower flux density level even by this method. In Table 3, we present the results of photometry of the *Spitzer* observations. The letter S in the last column indicates the highly saturated source and the letter G indicates the source listed in the GLIMPSE source catalogs.

For the 4 highly saturated sources, the *Spitzer* data (marked by an asterisk in Table 2) are not used. The 7 *Spitzer* data points of the 6 stars are used for the light curves (see Table 2). For the 2 stars (OH39.9+0.0 and OH45.5+0.1), the *Spitzer* data are not used for analysis but presented in the light curves as lower limits.

3. RESULTS AND DISCUSSION

In Figs. 1(a) to 1(d), we present *L* band light curves for the 12 stars. The data points are marked by different symbols for each observation and the best fitting sinusoidal curve is marked by a solid line in each panel.

We performed the light curve fitting using the observational data at *L* band for 12 sample stars. For curve-fitting of the observation data, we have used the Marquardt-Levenberg algorithm to find the coefficients of the individual variables. This algorithm gives the best fit values between the sinusoidal equation and the data. By analyzing the light curves, we determine the new pulsation parameters. We assume that there is no long-term trends caused by a secondary period within the time range of collected observational data. The data points that do not follow the common trend are not used for determination of the pulsation parameters. The unused data points for analysis are marked by parenthesis in Table 2 and the light curves.

For OH 42.3-0.4, we do not use a data point from Gehrz et al. (1985) because of large uncertainty. Gehrz et al. had examined the probabilities for source confusion, and found that OH 28.7-0.6 and OH 42.3-0.2 are faint enough at *L* band to be confused with field stars. Although the data have possibility for confusion, all data follow the general trend except one data point

*http://www.astro.wisc.edu/sirtf/docs.html.

†http://irsa.ipac.caltech.edu/index.html.

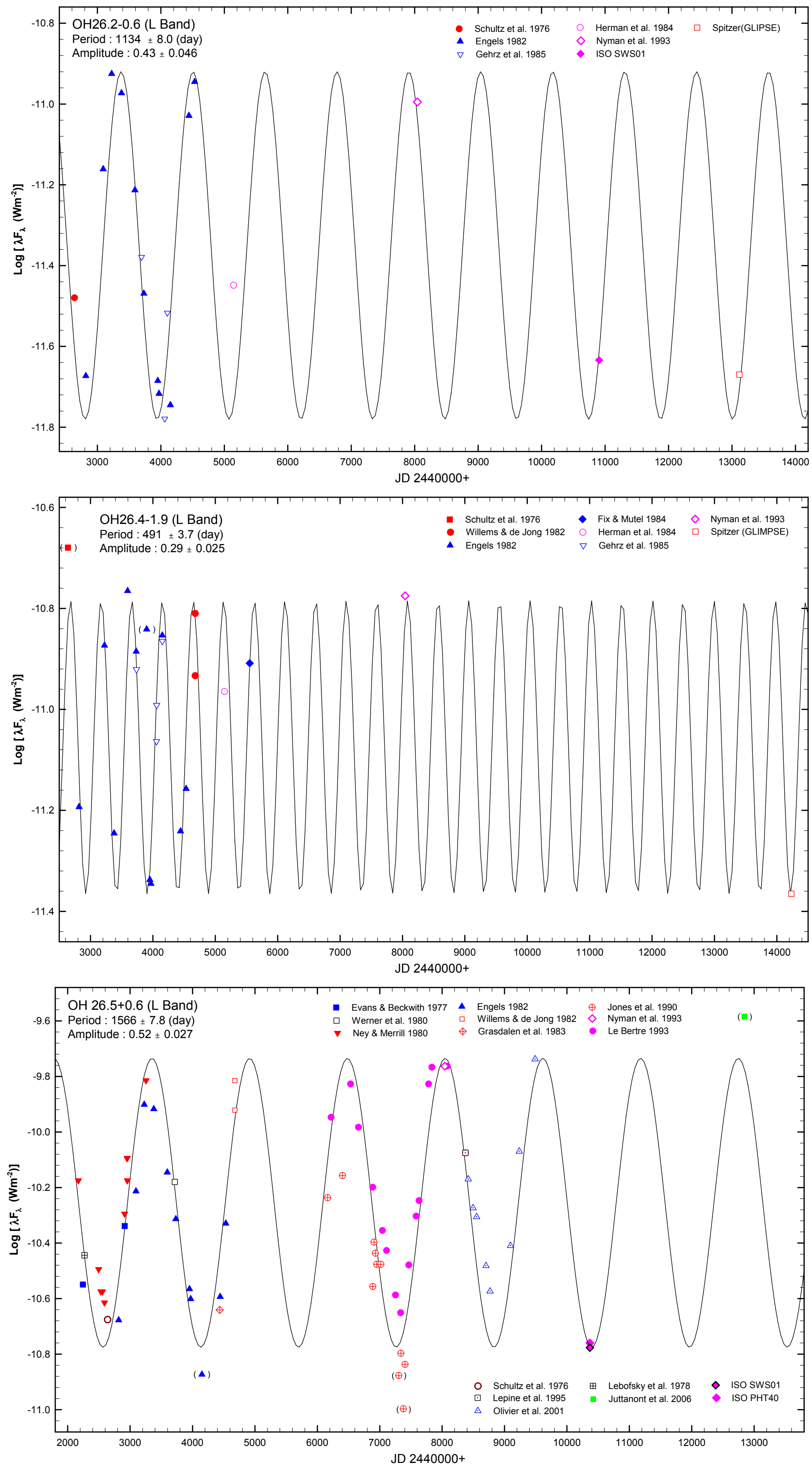

Fig. 1(a).— L band light curves of OH/IR stars

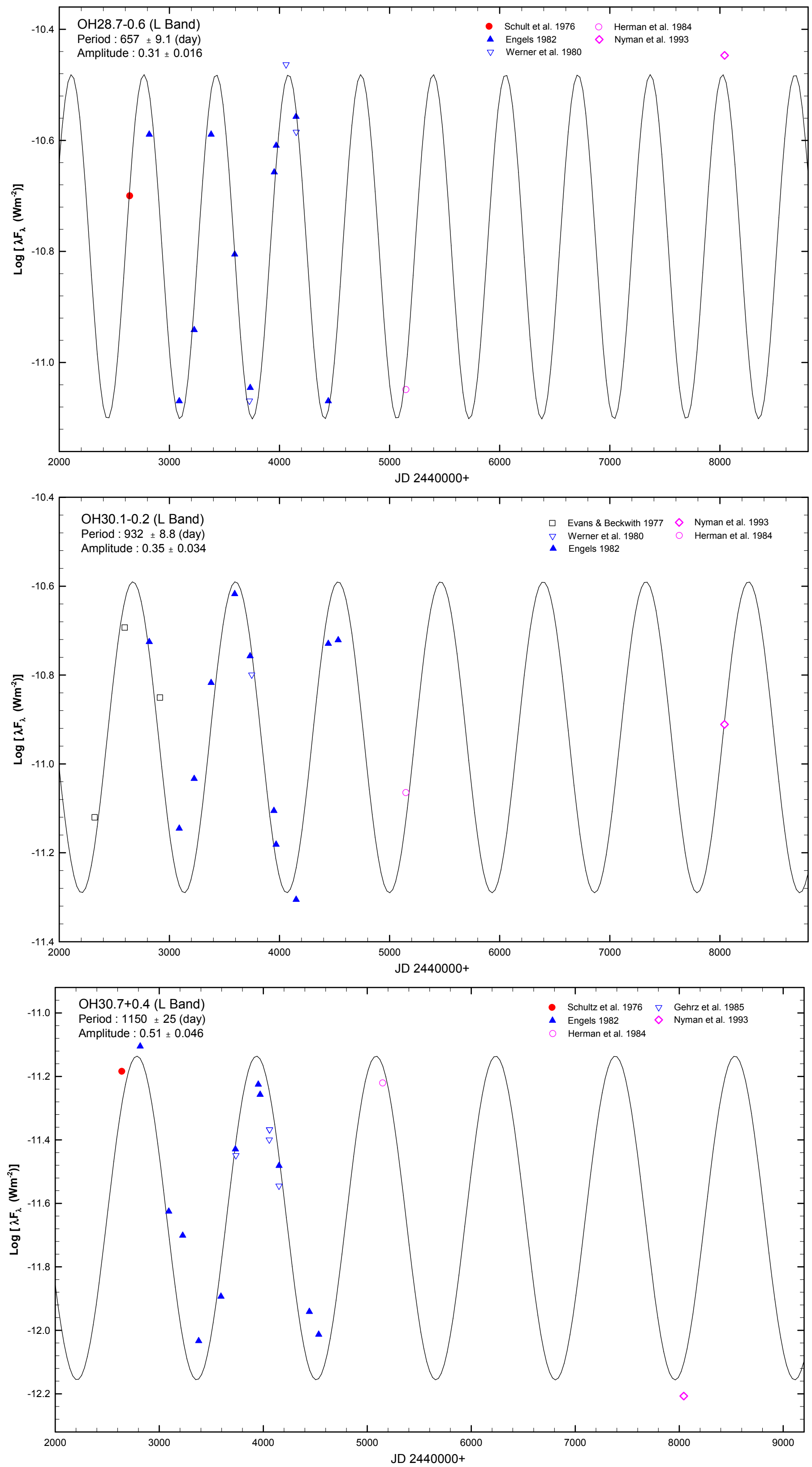

Fig. 1(b).— (continued)

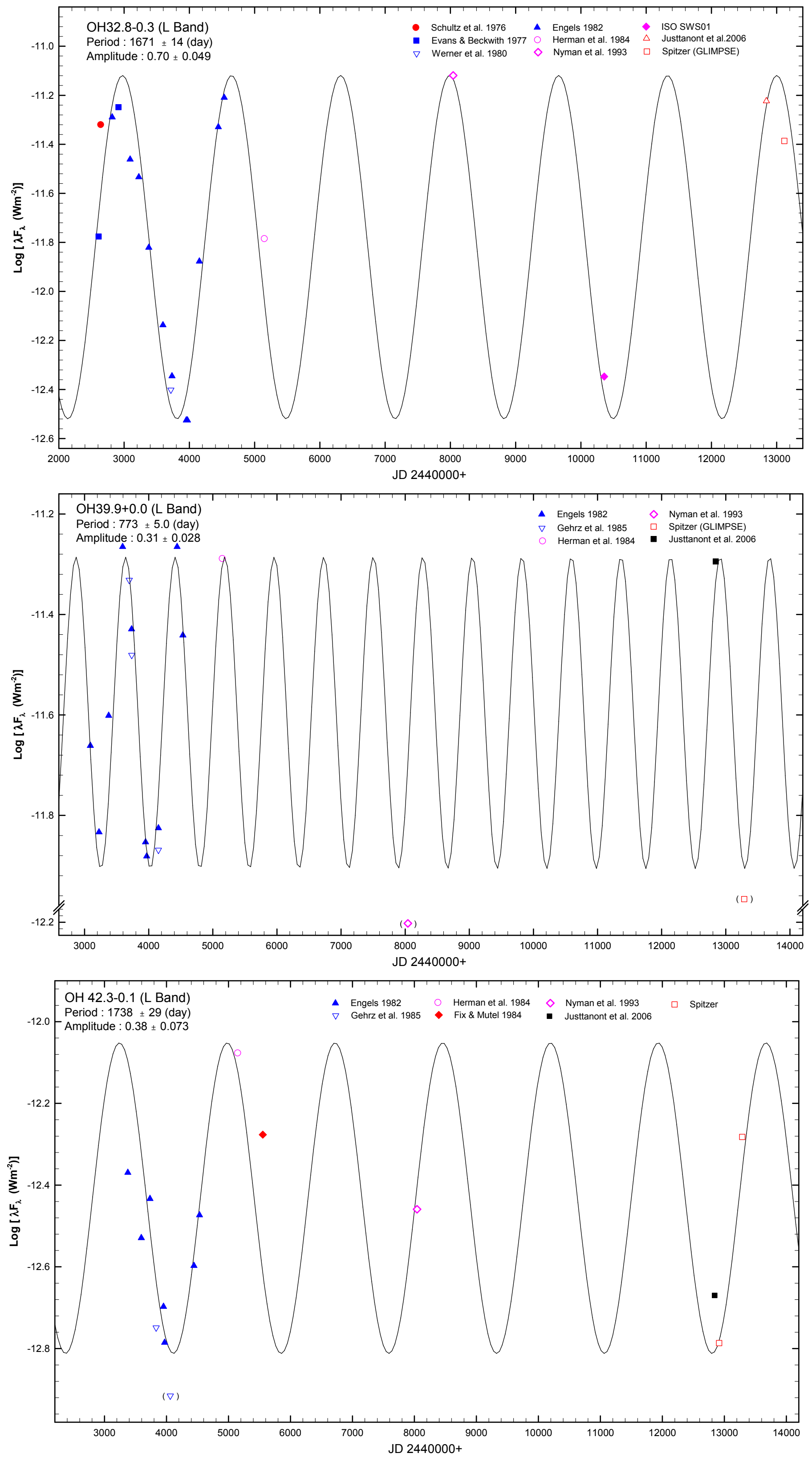

Fig. 1(c).— (continued)

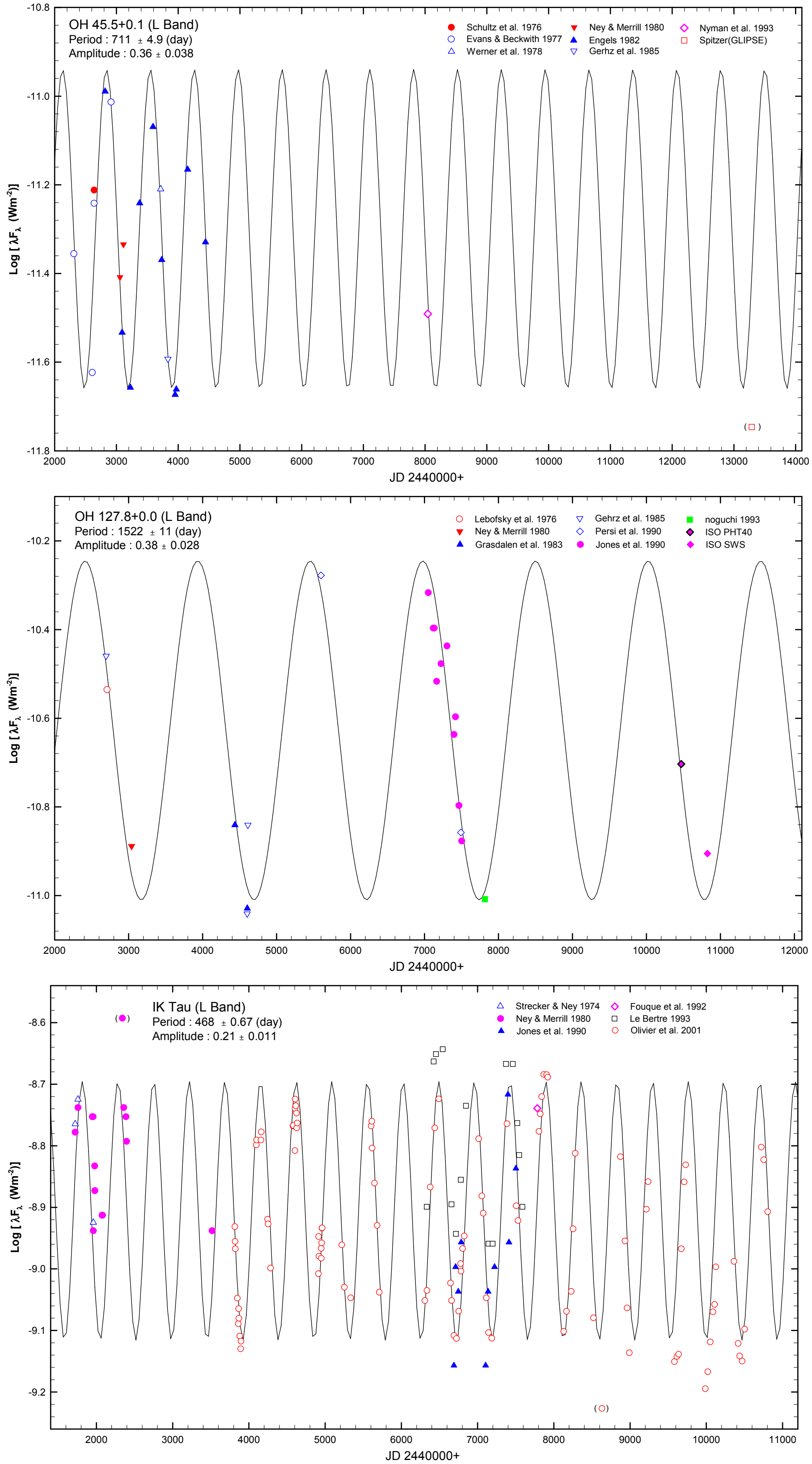

Fig. 1(d).— (continued)

Table 4.
New periods and amplitudes

Object	Period [days]			Amplitude [mag]			$\overline{m}$ [mag]
	This work	Previous work	Radio	This work	Previous work	Radio	This work
OH26.2	1134±8.0	1330±50	1181±13	2.2±0.2	2.05	1.05	4.28±0.16
OH26.4	491±3.7	540±20	652±26	1.5±0.1	1.45	0.44	3.59±0.11
OH26.5	1566±7.8	1630±100	1566±16	2.6±0.1	2.43	1.13	1.51±0.09
OH28.7	657±9.1	640±10	627±17	1.6±0.1	1.28	0.83	2.86±0.07
OH30.1	932±8.8	970±40	853±21	1.8±0.2	1.72	0.81	3.23±0.13
OH30.7	1150±25	1140±30	1039±27	2.6±0.2	2.32	0.57	4.99±0.18
OH32.8	1671±14	1750±130	1536±10	3.5±0.2	3.29	1.24	5.45±0.18
OH39.9	773±5.0	770±20	823±45	1.6±0.1	1.54	0.8	4.87±0.11
OH42.3	1738±29	1650±150	1945±83	1.9±0.4	1.04	0.36	6.96±0.30
OH45.5	711±4.9	720±20	760±31	1.8±0.2	1.71	0.92	4.13±0.12
OH127.8	1522±11	1537±18†	1994±130	1.9±0.1	2.15±0.2†	1.47	2.45±0.20
IK Tau	468±0.67	470±7‡	455.6±5.7	1.1±0.1	-	1.33	-1.86±0.04

† = Suh & Kim 2002; ‡=Hale et al. 1997.

observed at Kitt Peak National Observatory. This exceptional data was not used to determine the pulsation parameters.

A data point of OH 30.7+0.4 observed by Justtanont et al. (2006) is not used for the light curve analysis. The position of this stars in their paper is not matched with OH 30.7+0.4. It seems that they observed a different star (OH 30.55+0.28).

Table 4 lists the new pulsation parameters obtained in this paper and determined by previous authors for comparison. The pulsation parameters in the column of previous works were obtained from Engels et al. (1983) and those of the radio band were derived from the OH maser observations by Herman & Habing (1985). We use the parameters of 2 stars (OH 127.8+0.0 and IK Tau) from Suh & Kim (2002) and Hale et al. (1997), respectively. In this paper, we obtain the new parameters with much smaller standard deviation errors than previous works.

3.1 The Period and Amplitude Relation

Fig. 2 presents the period-amplitude relation (P-A relation) for 12 OH/IR stars obtained in this paper and 45 stars from previous investigations (Engels et al. 1983; Jones et al. 1990; Le Bertre 1993; Olivier et al. 2001). We find a linear P-A relation: $Amp(L) = 3.24 \times log(P_L) - 7.78$ obtained from 55 Mira LPVs. Data points unused due to high scatter from the general trend are marked by parenthesis. This relation at L band is generally similar to that of K band; $Amp(K) = 3.17 \times log(P_K) - 6.89$.

Contrary to paper I, there is no difference of the trends in the short and long period regions. This may be due to the molecular absorption effect at K band (see paper I).

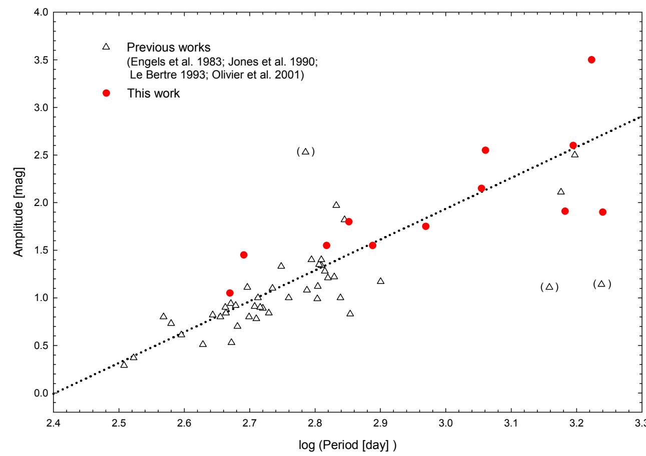

Fig. 2.— Period vs Amplitude at L band

3.2 The Comparison with the *IRAS* Color

Fig. 3 shows that the periods have a correlation with *IRAS* [12-25] colors. In Fig. 3, we present additional data from Chen et al. 2001. They show a large scatter. The period and [12-25] color reflect the mean density of a central star and the optical depth of dust shell, respectively. Therefore the correlation between period and IRAS color is the result of a dust shell driven by stellar pulsation. As an OH/IR star evolves with the increasing pulsation period, the dust shell would become thicker with the increasing IRAS [12-25] color. The large scatter in the correlation may be explained by the existence of a distribution of central stars with various masses and pulsation modes (Barthès & Luri 2001).

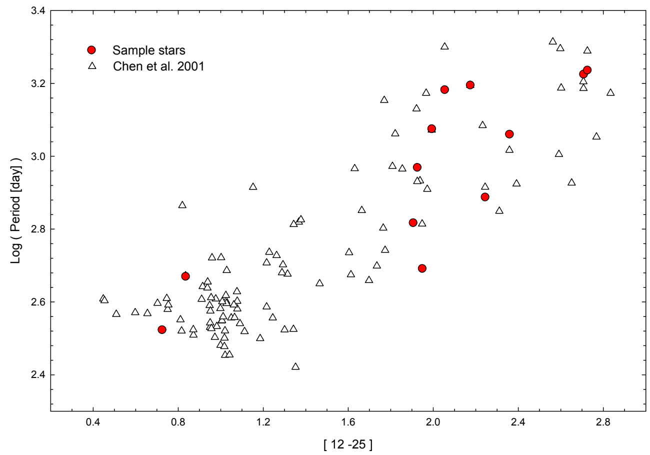

Fig. 3.— Period vs *IRAS* [12-25] color

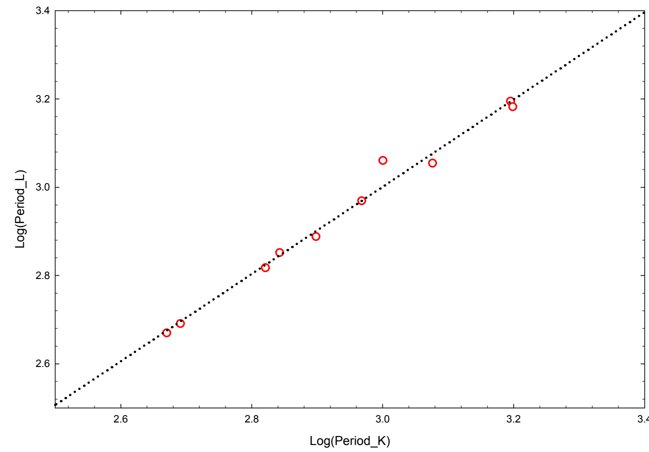

Fig. 4.— Periods at K and L band

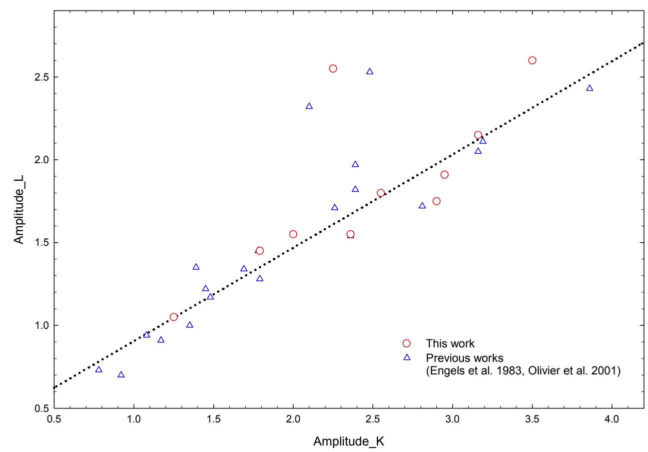

Fig. 5.— Amplitudes at K and L band

3.3 The Comparison with the K Band Data

The results at L band agree with the pulsation parameters at K band obtained in paper I. Figs. 4 and 5 display the periods and amplitudes of the eleven common sample stars presented in paper I.

The pulsation periods are very similar to those at K band. The relationship between periods from different bands is nearly linear; $log(P_K) = 0.9888 \times log(P_L) + 0.0346$. The only star showing a considerable difference is OH 30.7+0.4. This star has about 150 days longer period than that of K band. This discordant result could be due to low quality observational data as the source is quite faint at K band (10.38 to 12.48 mag).

The amplitude also show a linear relation between K and L bands. As is general in pulsating stars, the amplitudes at shorter wavelength (K band) appear to be larger than those at longer one (L band). There are 3 stars showing an appreciable difference in Fig. 5. These stars are faint sources (fainter than about 10.5 mag) at K band.

4. CONCLUSIONS

We have collected and analyzed the infrared observational data at L band for 12 OH/IR stars. The observation data cover about three decades including recent data from the *ISO* and *Spitzer*.

We have determined the pulsation parameters of the sample stars and compared them with previous results of the infrared and radio investigations. Because of the larger data base, the new pulsation parameters show much less errors than previous investigations. We find that the period-amplitude relation at L band shows no difference with the trends in the wide period region.

The effect of molecular lines at the L band wavelength region is relatively minor (Suh & Kwon 2009b). Therefore, the L band light curves would be more reliable for determining the pulsation parameters of OH/IR stars. We expect that future observations at L band would be helpful to improve our knowledge of OH/IR stars.

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