RADIATIVE PUMPING OF 1612 MHZ OH MASERS: OH/IR SOURCES WITH IRAS LRS SPECTRA AND 34.6 MICROMETER ABSORPTION FEATURE.

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ABSTRACT

The population inversion which leads to the 1612 MHz OH maser emission has long been thought to be radiatively pumped. Since OH rotational lines involved in this pumping scheme lie in the far–infrared they became observable only after the launch of the ISO satellite. With the aim to investigate the pumping conditions of the 1612 MHz OH maser emission in more details we have searched the ISO Archive for SWS observations around 34.6 μm of 1024 OH/IR sources with IRAS LRS spectra from compilation of Chen et al. (2001). Surprisingly, among 81 OH/IR sources which have appropriate SWS data only already reported objects: VY CMa, IRC+10420 and the Galactic center, show clear 34.6 μm absorption line. We discuss possible reasons for non–detection of this pumping line.

Key words: ISO – radiative pumping of the 1612 MHz OH maser.

1. INTRODUCTION

The first detection of intense radio emission from OH molecules was reported by Weaver et al. (1965) and soon an explanation based on maser amplification through induced processes was invoked (Litvak et al. 1966, Perkins et al. 1966). Shklovsky (1966) was first who proposed a radiative pumping mechanism for OH masers and his idea was elaborated in detail by Elitzur et al. (1976) for infrared (IR) stars which exhibit the 1612 MHz OH satellite line (hereafter OH/IR stars). In this scheme the required inversion of F=1 and F=2 sub-levels (even and odd parity, respectively) in the lowest rotational level is achieved by absorption of infrared photons (predominantly at 34.6 μm) from the ground state of OH molecule (2Π₁/₂ J=3/2) and consequent radiative decays to lower levels via far-infrared (FIR) transitions.

Due to atmospheric absorption in the FIR region, OH rotational lines are inaccessible from the ground and only indirect checks of the pumping scheme was possible using infrared flux extrapolated to about 35 μm. For example, it was shown that there are enough FIR photons (about 4 FIR photons for one OH photon - Elitzur 1992) to pump the 1612 MHz OH maser (Evans & Beckwith 1977, Nguyen-Q-Rieu et al. 1979, Epchtein et al. 1980). Direct confirmation of this theory become possible only with the launch of the Infrared Space Observatory (ISO, Kessler et al. 1996) which allows observation of the pumping transition(s) and other FIR OH lines from OH maser sources. First clear absorption at 34.6 μm in the Short Wavelength Spectrometer (SWS, de Graauw et al. 1996) spectrum of supergiant NML Cyg was reported by Justtanot et al. (1996) and in case of the Galactic center by Lutz et al. (1996). A detailed analysis supporting the radiative pumping cycle for circumstellar masers have been presented by Sylvester et al. (1997) in the case of another supergiant IRC+10420. They detected not only the pumping line at 34.6 μm in the SWS 02 spectrum of IRC+10420 (now resolved into Λ-doublet components), but also rotational cascade lines at 98.7, 163.1 and 79.2 μm. Thai-Q-Tung et al. (1998) performed modeling of pumping conditions and maser radiative transfer calculations for this supergiant. Their results are in agreement with the observed FIR OH lines, confirming the theoretical pump scheme. There are three more sources for which published SWS observations show absorption of the 1612 MHz pumping line at 34.6 μm. Namely, Neufeld et al. (1999) showed that this line is seen in the supergiant star VY CMa, Skinner et al. (1997) have reported its detection towards the ultra-luminous infrared galaxy Arp 220 and Bradford et al. (1999) have observed it in the starburst galaxy NGC 253. Summarizing, up to now there are 6 published detections of 34.6 μm absorption line from OH maser sources (from 3 supergiants: NML Cyg, IRC+10420, VY CMa, from 2 galaxies: Arp 220, NGC 253 and from the Galactic center).

In this paper we report on a search of the ISO Data Archive (IDA) for further evidence of absorption at 34.6 μm among OH/IR sources which were observed with the ISO SWS. In Section 2 we describe our working sample, present the 1612 MHz OH/IR sources which have available SWS observations around 34.6 μm, discuss briefly the SWS data reduction process and present examples of the SWS spectra for OH/IR sources with detected absorption line at 34.6 μm. Finally, in Section 3 we discuss briefly the results obtained.

2. OBSERVATIONS

Chen et al. (2001) discussed properties of the 1612 MHz OH sources associated with the InfraRed Astronomical Satellite (IRAS) counterparts which have Low Resolution
Table 1. Results of the IDA search for SWS data covering 34.6 μm region within 1 arcmin around IRAS position of OH/IR sources from list of Chen et al. (2001).

| IRAS name  | LRS classification | IDA name   | SWS AOT 01 | SWS AOT 02 | SWS AOT 06 | SWS AOT 07 |
|------------|--------------------|------------|------------|------------|------------|------------|
| 01037+1219 | E                  | WX Psc     | +          | +          | +          | +          |
| 01304+6211 | A                  | OH 127.8+0.0 | +          | +          | +          | +          |
| 02192+5821 | E                  | S Per      | +          | +          | +          | +          |
| 03507+1115 | E                  | IK Tau     | +          | +          | +          | +          |
| 05073+5248 | E                  | IRC+50137  | +          | +          | +          | +          |
| 05373+0810 | C                  |            |            |            |            |            |
| 05380−0728 | U                  |            |            |            |            |            |
| 05506+2414 | H                  |            |            |            |            |            |
| 06053−0622 | H                  | MON R2 IRS3 | +          | +          | +          | +          |
| 06238+0904 | C                  |            |            |            |            |            |
| 07027−7934 | H                  |            |            |            |            |            |
| 07209−2540 | E                  | VY CMa     | +          | +          | +          | +          |
| 10197−5750 | H                  | Roberts 22 | +          | +          | +          | +          |
| 10580−1803 | E                  | R Crt      | +          | +          | +          | +          |
| 13157−6515 | E                  |            |            |            |            |            |
| 15452−5459 | U                  |            |            |            |            |            |
| 15559−5546 | P                  |            |            |            |            |            |
| 16235+1900 | E                  | BS 6119    |            |            |            |            |
| 16279−4757 | H                  |            |            |            |            |            |
| 16280−4008 | H                  | NGC 6153   | +          | +          | +          | +          |
| 16342−3814 | H                  |            |            |            |            |            |
| 17004−4119 | A                  |            |            |            |            |            |
| 17010−3840 | A                  |            |            |            |            |            |
| 17103−3702 | L                  | NGC 6302   | +          | +          | +          | +          |
| 17150−3224 | H                  |            |            |            |            |            |
| 17319−6234 | E                  |            |            |            |            |            |
| 17347−3139 | H                  |            |            |            |            |            |
| 17360−3012 | E                  |            |            |            |            |            |
| 17393−3004 | U                  | 1742−3005  | +          | +          | +          | +          |
| 17411−3154 | A                  | AFGL 5379  | +          | +          | +          | +          |
| 17418−2713 | A                  |            |            |            |            |            |
| 17424−2859 | H                  | GC Sgr A*  | +          | +          | +          | +          |
| 17430−2848 | H                  | GCS 3 I    | +          | +          | +          | +          |
| 17431−2846 | H                  | G0.18−0.04 | +          | +          | +          | +          |
| 17443−2949 | A                  |            |            |            |            |            |
| 17463−3700 | F                  | H1−36      |            |            |            |            |
| 17501−2656 | E                  | AFGL 2019  | +          | +          | +          | +          |
| 17516−2526 | U                  |            |            |            |            |            |
| 17554+2946 | E                  | AU Her     | +          | +          | +          | +          |
| 17574−2403 | H                  | W82A2      | +          | +          | +          | +          |
| 18050−2213 | E                  | VX Sgr     | +          | +          | +          | +          |
| 18095+2704 | H                  |            |            |            |            |            |
| 18123+0511 | F                  |            |            |            |            |            |
| 18139−1816 | I                  | OH 12.8−0.9 | +          | +          | +          | +          |
| 18196−1331 | A                  | GL 2136    | +          | +          | +          | +          |
| 18257−1000 | A                  | OH 21.5+0.5 | +          | +          | +          | +          |
| 18276−1431 | H                  | OH 17.7−2.0 | +          | +          | +          | +          |
| 18348−0526 | A                  | OH 26.5+0.6 | +          | +          | +          | +          |
| 18349+1023 | E                  | V1111 Oph  | +          | +          | +          | +          |
| 18385−0617 | A                  | OH 26.2−0.6 | +          | +          | +          | +          |
| 18460−0254 | A                  | OH 30.1−0.7 | +          | +          | +          | +          |
| 18488−0107 | A                  | OH 32.0−0.5 | +          | +          | +          | +          |
| 18498−0017 | H                  | OH 32.8−0.3 | +          | +          | +          | +          |
| 18549+0208 | A                  | OH 35.6−0.3 | +          | +          | +          | +          |

Spectra (LRS) available. Altogether this sample consists of 1024 OH/IR sources for which the difference between OH maser and IRAS position is smaller than 1′. These sources were classified according to the Volk & Cohen (1989) classification scheme and it was found that sources with silicate emission (class E) form the largest group (about 57%) followed by the group with silicate absorption (class A: about 16%) and by group of sources with red-continuum (class H: about 6%). Information about LRS classification (i.e. about optical depth at least in the case of E and A sources) was intended to be used for interpretation of the 34.6 μm absorption line detection frequency in our sample of OH/IR sources.

We have searched the IDA for SWS data within 1 arcmin around IRAS position of 1024 galactic OH/IR sources from Chen et al. (2001) list (NML Cyg is not included in our sample as there is no IRAS observations for this supergiant, while Arp 220 and NGC 253 are extragalactic mega-maser sources). The results of our search for SWS data around 34.6 μm are given in Table 1. The associated IRAS name is given in column 1, IRAS LRS spectrum classification in column 2 and most frequently used source name from the original ISO proposals (if different from the IRAS one) in column 3. Sign + in columns 4, 5, 6 and
7 means that at least one SWS spectrum, covering wavelengths range around 34.6 µm, taken with Astronomical Observation Template (AOT) 01, 02, 06 and 07, respectively, is available. In some cases (e.g. GC Sgr A*) there are many SWS spectra available inside a 1′ circle around IRAS position. All of them were carefully checked but a complete analysis will be published elsewhere.

The ISO SWS 01, 02, 06 and 07 data (offline processing – OLP version 9.5) analyzed in this work were all processed using ISAP (ISO Spectroscopic Analysis Package) version 2.1. Recently, a new versions of OLP (10.0, 10.1) have been released, but these newer data should not change our conclusions as far as the detection/non-detection frequency of the 34.6 µm absorption line is concerned. Data analysis consisted of extensive bad data removal primarily to minimize the effects of cosmic rays. First, all detectors were compared to identify possibly narrow features and then the best detector was chosen to compare one by one with others during the process of bad data removal. However, there are usually fewer scans in SWS 07 data than in other AOT’s, so all scans were processed simultaneously in these cases. In the next step the spectra were scaled to the same flux level to correct for different responsivities of the detectors and any remaining outliers removed. When scaling, spectra were shifted by the offset mode if their overall flux density was lower than about 100 Jy, while by the gain mode when they had flux density higher than this limit. For SWS 06 spectra, the two scan directions correspond to two different lines and it is not possible to shift them simultaneously within ISAP. Therefore, scaling was done for the two directions separately. In addition, whenever memory effects or irregularities were present in the two scans of SWS 01 or 02 data, we averaged them separately and the resulting two sub–spectra were used to check reality of possible features. Finally, spectra were averaged across detectors, scans and lines (if applicable), using median clipping to discard points that lay more than 2.5σ from the median flux. Spectra were averaged typically to resolution of 400, 500, 800 and 1500 for SWS 01 data taken with speed 01, 02, 03 and 04, respectively, and to resolution of 3000 (SWS 02), 1500 (SWS 06) and 30000 (SWS 07) for the other observation modes. Finally, when the 34.6 µm absorption line was detected we used ISAP to determine continuum level and fit a single Gaussian profile to estimate line parameters. Only in case of the 34.6 µm line which was resolved into Λ–doublet components we fit Gaussian profile to each of them.

Altogether, we have processed 159 SWS spectra (114 for AOT 01; 21 for 02; 16 for 06 and 8 for 07) around 34.6 µm for 81 OH/IR sources which have IRAS LRS spectra. The 34.6 µm absorption feature was undoubtedly detected in the SWS spectra taken toward only 3 OH/IR sources from our sample: supergiant VY CMa (IRAS 07209−2540); supergiant IRC+10420 (IRAS 19244+1115) and the Galactic center (IRAS 17424−2859). In Figs.1–3 we present examples of unpublished spectra for these 3 sources.
Table 2. Observational details for sources with detected 34.6 µm absorption line.

| source name | Obs. mode | TDT | n_{34.6} 10^3 [m^{-2} s^{-1}] | n_{OH} 10^2 [m^{-2} s^{-1}] |
|-------------|-----------|-----|-----------------------------|-------------------------------|
| VY CMa      | 07        | 73601963 | 14.1+17.9 | 1597\(^1\) |
|             | 06        | 73402218 | 45.8     |                               |
| IRC+10420   | 07        | 36401613 | 10.4+9.9 | 620\(^2\)                     |
|             | 06        | 31600936 | 7.3      |                               |
| GC Sgr A*   | 01(04)    | 09500203 | 18.4     | 41.3\(^3\)                    |

\(^1\)Neufeld et al. (1999); \(^2\)Sylvester et al. (1997); \(^3\)Derived from 17 maser sources (Sjouwerman et al. 1998) which are located within 1 around IRAS17424–2859 position. For SWS 07 observations n_{34.6} is given as a sum of two numbers which correspond to each \Lambda–doublet component. Number in parenthesis denote speed of SWS 01 observations.

A detailed discussion of all detections (including tentative ones) for the more complete sample of OH/IR sources will appear elsewhere. Information about presented spectra, the obtained number of 34.6 µm photons (n_{34.6}) and number of the OH photons (n_{OH}) are given in Table 2.

3. DISCUSSION

As we discussed in Introduction the theory of radiative pumping of the 1612 MHz OH maser emission seems to be well established. In addition, pump rates (n_{OH}/n_{34.6}) determined from the ISO SWS spectra analyzed here (5% – TDT 73601963 and 3.5% – TDT 73402218 for VY CMa; 3.1% – TDT 36401613 and 8.5% – TDT 31600936 for IRC+10420 but only 0.2% – TDT 09500203 for the Galactic center) do not contradict the proposed pumping scheme which requires about 4 FIR photons for one OH photon. Therefore, it is surprising that there are only 3 cases among 81 OH/IR sources with appropriate ISO SWS data which show a clear absorption at 34.6 µm.

Certainly, the detection rate of the 34.6 µm pumping line depends on the signal to noise ratio of the SWS spectra. Sources with tentative detection of this absorption line (not discussed here) have rather noisy spectra and it is difficult to prove the reality of the line. In any case, the number of sources with tentative detections is rather small and low signal to noise ratio does not probably solve the problem of the 34.6 µm line non-detection in other sources with good signal-to-noise SWS spectra around 35 µm. Another factor which could influence the detection of this absorption feature is the spectral resolution. However, among analyzed data there are spectra with high resolution (SWS 01 speed 4, SWS 02, SWS 06 and, especially, SWS 07) which do not show absorption at 34.6 µm. The detection rate also does not depend on the source flux. In our sample we have sources with flux at 34.6 µm well in excess of 1000 Jy and still there is no signature of any absorption at 34.6 µm.

Therefore, we believe that explanation of this puzzling result is related to the geometry (relative location and size) of masering and dusty regions and/or to differences in physical conditions inside circumstellar (or interstellar) shells (clouds). Possibly, regions containing masering OH molecules (OH spots) are much smaller than regions emitting IR photons and absorption at 34.6 µm is filled by more spatially extended IR emission. However, the fact that the 34.6 µm absorption line is seen only in supergiants and in the extragalactic sources (Galactic center is very likely to be similar to the later cases) is probably not a coincidence and requires more careful analysis of physical conditions around sources with detected and non-detected 34.6 µm pumping line. More detailed discussion based on sample of all known galactic OH/IR sources with IRAS identification will appear elsewhere.

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