Polarisation Observations of \( \text{H}_2\text{O} \ J_{K_\text{a}-1K_\text{b}} = 5_{32} - 4_{41} \) 620.701 GHz Maser Emission with HERSCHEL*/HIFI in Orion KL (Research Note)

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ABSTRACT

Context. The high intensities and narrow bandwidths exhibited by some astronomical masers make them ideal tools for studying star-forming giant molecular clouds. The water maser transition \( J_{K_\text{a}-1K_\text{b}} = 5_{32} - 4_{41} \) at 620.701 GHz can only be observed from above Earth’s strongly absorbing atmosphere; its emission has recently been detected from space.

Aims. We sought to further characterize the star-forming environment of Orion KL by investigating the linear polarisation of a source emitting a narrow 620.701 GHz maser feature with the heterodyne spectrometer HIFI on board the Herschel Space Observatory.

Methods. High-resolution spectral datasets were collected over a thirteen month period beginning in 2011 March, to establish not only the linear polarisation but also the temporal variability of the source.

Results. Within a 3\( \sigma \) uncertainty, no polarisation was detected to an upper limit of approximately 2\%. These results are compared with coeval linear polarisation measurements of the 22.235 GHz \( J_{K_\text{a}-1K_\text{b}} = 6_{16} - 5_{15} \) maser line from the Effelsberg 100-m radio telescope, typically a much stronger maser transition. Although strongly polarised emission is observed for one component of the 22.235 GHz maser at 7.2 km s\(^{-1}\), a weaker component at the same velocity as the 620.701 GHz maser at 11.7 km s\(^{-1}\) is much less polarised.

Key words. masers - magnetic fields - polarization

1. Introduction

The Kleinmann-Low nebula in the Orion Molecular Cloud 1 (OMC-1) is a high-mass star-forming region, the nearest such region in our Galaxy at 418\,pc \( (\text{Kim et al. 2008}) \). Its line-of-sight velocity relative to the local standard of rest (LSR) is about 9 km s\(^{-1}\) \( (\text{Garay et al. 1989}) \). Since the discovery of the 22.235 GHz water maser transition in the Orion Molecular Cloud \( (\text{Cheung et al. 1969}) \), the region has frequently been studied also at higher frequency maser transitions. Recently, \text{Neufeld et al.} \( (2013) \) mapped the theoretically predicted \( J_{K_\text{a}-1K_\text{b}} = 5_{32} - 4_{41} \) 620.701 GHz transition in the Kleinmann-Low Nebula (Orion KL) with Herschel/HIFI. Combining their observations with co-located 22.235 GHz Effelsberg data, they were able to verify a maser pumping model arising from collisional excitation and spontaneous radiative decay \( (\text{Neufeld & Melnick 1991}) \). Hereafter, we will mostly refer to these frequencies as 22 GHz and 621 GHz.

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The first astronomical detection of the 621 GHz maser transition of ortho water vapor \( (\text{Neufeld & Melnick 1991}) \) was made by \text{Harwit et al.} \( (2010) \). It appeared to exhibit a polarisation of approximately 2\% toward the oxygen-rich supergiant star VY Canis Majoris, and was a few times less luminous than the star’s ortho-H\(_2\)O 22 GHz maser. The aforementioned study of \text{Neufeld et al.} \( (2013) \) presented the first detection of this transition in an interstellar region (i.e., Orion KL). Their maps of this region revealed a spatially localized source emitting a strong, spectrally narrow emission feature at 621 GHz. Their discovery of this feature gave rise to the present attempt to determine whether the 621 GHz feature might be linearly polarised. In a later search through the Herschel archives \( (\text{Neufeld et al. 2013}) \) also found similarly narrow 621 GHz emission features emanating from the Orion South condensation and the W49N region of high-mass star formation. By then, however, the Herschel mission was ending and a search for signs of polarisation in these features were no longer possible. To date, the Heterodyne Instrument for the Far Infrared (HIFI) \( (\text{de Graauw et al. 2010}) \) onboard the Herschel Space Observatory \( (\text{Pilbratt et al. 2010}) \) has been the sole facility capable of linear polarisation studies of spec-

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tral lines at this frequency. Complementary circular polarisation studies, however, have remained beyond reach.

Between March 2011 and April 2012, we obtained six sets of observations of the 621 GHz line along a sight line toward Orion KL, with the Herschel/HIFI instrument. We complemented these with observations of the 22 GHz line taken contemporaneously with the Max-Planck-Institut für Radioastronomie (MPIfR) 100-m telescope in Effelsberg, Germany. In Section 2 we report the results of these observations. We next present our polarisation results in Section 3 along with a depiction of the temporal behaviour of the maser line over this year-long period. Finally, Section 4 presents our conclusions, while the tabular summaries of our observations, our maps of the 621 GHz water maser, and a further discussion on pointing errors can be found in Appendices A, B, and C (on line material).

2. Observations

2.1. HIFI Observations

HIFI enables observations in fourteen frequency bands. We observed the 621 GHz transition in HIFI Band 1B, which covers the range from 562.6 to 628.4 GHz. Like all of the other HIFI bands, Band 1B houses two channels sensitive to linearly polarised radiation, respectively, in the horizontal (H) and vertical (V) directions. The two channels exhibit peak sensitivities along directions at angles of 82.5° (H) and -7.5° (V), relative to the Herschel spacecraft’s y-axis, kept close to perpendicular to the ecliptic plane at all times. On the sky, the H- and V-beams are offset from each other by 6′/6, a non-negligible fraction of the 34′/4 full-width-half-magnitude (FWHM) beam at 620.701 GHz. Due to potential beam pointing errors, small offsets in the H- and V-beam from their intended positions may be expected, leading to uncertainty in the mean beam pointing direction. At the time of writing this was constrained to between 0′×8 – 0′×9 (1σ).

Observations were conducted beginning on 14 March 2011 when a small map was acquired using the HIFI “on-the-fly mapping” (OTF) mode, as part of the HEXOS Guaranteed Time Key Program (PI: E. Bergin). A total of fifteen Nyquist-sampled pointings were implemented in a rectangular, 5 by 3 configuration. Spectral data were obtained with the digital autocorrelation high-resolution spectrometer (HRS) and the wide-band spectrometer (WBS). The map was centered at (R.A.[J2000]=05h35m13s, decl.[J2000]=−05°22′00″.5), and spanned ± 21′/3 in Right Ascension and ± 53′′ in Declination. Individual pointings were separated by ± 10′/5 in R.A. and ± 13′′ in Declination. The spectral resolution in the HRS mode was 0.125 MHz, or, equivalently, a line-of-sight velocity resolution of 0.06 km s⁻¹. The WBS resolution was ± 1 MHz or ± 0.5 km s⁻¹. All observations used an OFF-source reference position located 14′ from the maser location.

Following the mapping of 14 March 2011, two pointed observations were obtained that year, respectively, on 26 March and 8 April. Over this period the source rotated by ≃ 14° about the spacecraft line-of-sight. Observations obtained at different times were necessary since a minimum of two sets of measurements at separate source rotation angles are required for polarisation analysis (Harwit et al. 2010). For pointed observations the central point on the line separating the H- and V-beam centers was directed at two successive positions on the sky, in position switching mode, in order to place the center of the H polarisation beam for a given integration to coincide with the center of the V polarisation beam for the subsequent integration – thus compensating for the misalignment between the beams.

After a preliminary analysis, follow-up observations were executed on 25 February and 14 April 2012. The first of these, performed in position switching mode, were centered at the same position cited above. Thereafter, on 14 April, the last of the pointed measurements was obtained, followed on the same day by a small map of the same dimensions as that of 14 March 2011. While the 2011 observations lasted 888 s, integrations in 2012 were extended to 1683 s in order to reduce the overall noise. The entirety of the investigation is summarised online in Table A.1.

2.2. Effelsberg Observations

Ground-based observations were undertaken with the 100-m Effelsberg radio telescope in tandem with the HIFI observations of 2011 and 2012. Centered at 22 GHz, the JConnectionFactory×K = 60−523 transition of ortho water vapour, our observations consisted of linear polarisation signals obtained from two orthogonal channels of the K-band (1.3 cm) receiver located at the primary focus of the telescope. The Effelsberg beam profile can be approximated as a Gaussian with a FWHM of 41″/7. The frequency resolution of each dataset was 6.104 kHz, corresponding to a velocity resolution of 0.082 km s⁻¹, and the spectra were calibrated using corrections for gain-elevation and atmospheric attenuation.

Our measurements were composed of pairs of scans obtained at different source parallactic angles in each of the years 2011 and 2012. In 2011, the first scan at 17:45 UT on 21 March, lasting one hour, was followed by a second scan recorded at 20:09 UT the same day, the source having rotated by approximately 23° by then. In 2012, pairs of observations were taken on 21 March and 18 April with corresponding source parallactic angle rotations of ≃ 67° and ≃ 16°, respectively. All of these pointed observations were collocated with the HIFI center position. At the same epochs, maps were also produced that were useful in more accurately describing the maser environment. A complete summary of the Effelsberg data is provided online in Table A.2.

3. Methods/Results

3.1. Polarisation Analysis

As explained in Harwit et al. (2010), HIFI does not provide regular 45° spacings with which the computation of the Stokes Q and U parameters is simplest. Instead, we must rely on the position angles (PA) listed in Table A.1 for the vertical polarisation direction, with the horizontal axis at PA + 90°. The Stokes Q and U can then be calculated using the analysis detailed in Harwit et al. (2010), from which the polarisation fraction and angle are evaluated with

\[
p = \sqrt{Q^2 + U^2}/I, \quad \theta = 0.5 \arctan(U/Q),
\]

respectively, with I the total intensity. As explained below, this analysis has been applied to our entire set of HIFI 621 GHz data, with the 2011 and 2012 data sets combined to yield a single polarisation result of sufficient precision. The Effelsberg 22 GHz measurements were not affected by the same constraints and were considered separately for the respective 2011 and 2012 data sets.

3.2. HIFI data

The entire suite of observations listed online in Table A.1 was considered, although only the center position of each of the maps
we found all pointings to lie within switching and OTF observations. Throughout our observations the beam is accurate to within 0.′′19 Feb 2012 (Observation Day 1011) the reported center of datasets of 2012 reduced the noise in polarisation intensity (2011. When combined with the 2011 data the three additional and intensity was strongest, was selected for analysis. All data were moved, to feature the maser line. From epoch to epoch there were polarisation in the maser emission is apparent from the absence of the analysis after removal of the broad component; the lack of polarisation signatures above three standard deviations in the 3.2.1, this assumption is consistent with the fact that we found (i.e., point-like) source in the region. As is discussed in Section systematically have an intensity that varies strongly on relatively short time scales: it is thought that such turbulent enviroments, with their large velocity gradients, can induce more frequent fluctuations in intensity with changes in the velocity of the emission line (Stahler & Palla 2004).

3.2.1. Pointing Effects on Masers Polarisation Measurements

We performed the same polarisation analysis discussed in Section 3.1 on a simulated spectrum to quantify the effect of our pointing uncertainties on measured maser polarisation signals. To do so the beam profile was approximated by a Gaussian function matching the FWHM of the HIFI beam at 620.701 GHz (34′′4), while the source was considered unpolarised and of no spatial extent (simulating a maser point source). Each simulated measurement was associated with one of our HIFI observations (see Table A.1), including random pointing errors of about 3′′, such as might reasonably be expected for HIFI. The peak intensity of a given measured spectrum would thus decrease as the pointing position drifted away from the source’s location. This analysis revealed weak polarisation levels averaging ~ 0.7%, consistent with the aforementioned upper limit resulting from our HIFI observations.

Although we cannot rule out the possibility that the total intensity of the 621 GHz maser flux we measure originates from the contributions of several spatially unresolved sources, our simple simulation seems to imply a lack of spatial extent for the overall maser emission, as compared to the HIFI beam. This feature allows for precise polarisation measurements when the pointing errors are sufficiently small. However, the same is not true for the broad component of the 621 GHz water maser line in view of potential source variations with pointing positions, as discussed in the online Appendix C.

3.3. 22 GHz (Effelsberg) Data

The 22 GHz Effelsberg data, obtained during the same periods (although not precisely coeval), do not appear to be affected by the same source of emission responsible for the broad component in the 621 GHz transition. However, we also observed significant change in intensity on timescales of one to several months (i.e., between respectively 21 March 2012 and 18 April 2012, and 21 March 2011 and 18 April 2012), which imply some intrinsic source evolution with time. We find that the strongest component at 7.2 km s⁻¹ varies from ≃ 1.2×10⁴ K to ≃ 2.1×10⁴ K (or from 14 kJy to 26 kJy). These variations are in line with other observations performed at the position of peak intensity of the 22 GHz maser (located some ≃ 15″ east and ≃ 36″ south from our pointed observations) during approximately the same time period. More precisely, interferometric observations
of Matveyenko et al. (2013) revealed significant outburst activity between July 2011 to May 2012 while tracking the evolution of velocity components at 7.0 km s\(^{-1}\) and 7.6 km s\(^{-1}\). Previously, in February 2011, Hirota et al. (2011) recorded a flare reaching an intensity of 44 kJy using the VLBI Exploration of Radio Astrometry interferometer. While, unlike our study, these observations were conducted at very high spatial resolutions (\(\sim 1\) mas), single-dish observations of Otto & Gaylard (2012) at approximately 120\(^{\prime}\) resolution also detected strong flares reaching as high as 80 kJy during an eight-month period spanning from March to November 2011.

We performed a polarization analysis on each of our Effelsberg data sets and found that the polarization levels did not appreciably change over the different epochs. Figure 2 shows the results of the analysis for the 21 March 2011 data. The top panel displays the Stokes I spectra, along with several linear polarization measures, while the bottom panel shows the polarization flux and angles. Most noticeable are the high polarisation levels, of order 75\% at the center of the 7.2 km s\(^{-1}\) feature. Elsewhere, the polarisation level is rather constant in the 3 – 5\% range, except for the second strongest feature at \(\sim 11.7\) km s\(^{-1}\), where levels exceed 10\%. While there have been previous detections of polarisation of comparable levels (Horiuchi & Kameya 2000; Garay et al. 1989), the aforementioned contemporaneous interferometric observations of Matveyenko et al. (2012) revealed lower polarization levels of about 55\% at 7.65 km s\(^{-1}\).

4. Conclusion

We have reported the astronomical detection of the 621 GHz \(J_{\kappa_{\text{H}_2O}} = 5_{32} \rightarrow 4_{21}\) transition of the ortho H\(_2\)O maser in the star-forming region Orion KL, which was also recently discussed by Neufeld et al. (2013). In observations with the Herschel/HIFI instrument the maser was found not to be linearly polarised to a 3\(\sigma\) upper limit of \(\sim 2\%\). Low polarisation levels for water masers are not inconsistent with expectations from the mechanism of Goldreich, Keeley and Kwan (Goldreich et al. 1973), at least in the absence of radiative saturation (Watson 2009). These results are also approximately in line with the low polarisations of a few percent found by Harwit et al. (2010).

Polarisation measurements of the HIFI data were complicated by the strengthening of a broad pedestal component in data from 2011 to 2012. We concluded that this feature is likely to be the result of pointing artifacts. Attempts were also made to settle the change in maser line strengths between the two observing epochs but the question remains to be resolved.

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Appendix A: Summary of Herschel/HIFI and Effelsberg Observations

Table A.1. Summary of HIFI observations conducted in 2011 and 2012.

| Observation Number | Observation Day (OD) | Observation ID (ObsID) | Date       | System Temperature $T_{\text{sys}}$ (K) (V/H) | Position Angle ( PA (°) | Mode            |
|--------------------|----------------------|------------------------|------------|-----------------------------------------------|-------------------------|-----------------|
| 1V/H               | 666                  | 1342215918-9           | 2011 Mar 3 | 97/98                                        | 266.2                   | OTF Mapping     |
| 2V/H               | 666                  | 1342215920-1           | 2011 Mar 3 | 97/97                                        | 266.2                   | OTF Mapping     |
| 3V/H               | 681                  | 1342216838-9           | 2011 Mar 26| 97/97                                        | 273.6                   | Pointed         |
| 4V/H               | 694                  | 1342218904-5           | 2011 Apr 8 | 97/98                                        | 280.0                   | Pointed         |
| 5V/H               | 1017                 | 1342239637-8           | 2012 Feb 25| 68/84                                        | 258.9                   | Pointed         |
| 6a-V/H             | 1066                 | 1342244409-10          | 2012 Apr 14| 68/84                                        | 284.1                   | Pointed         |
| 6b-V/H             | 1066                 | 1342244411-2           | 2012 Apr 14| 68/84                                        | 284.1                   | OTF Mapping     |

Notes. (a) Position of the HIFI vertical polarisation axis relative to north, increasing eastward.

Table A.2. Summary of Effelsberg observations conducted in 2011 and 2012.

| Observation Number | Date       | System Temperature $T_{\text{sys}}$ (K) (V/H) | Parallactic Angle (PA (°)) | Mode   |
|--------------------|------------|-----------------------------------------------|----------------------------|--------|
| 1a-V/H             | 2011 Mar 21| 91/81                                         | 6.1                        | Pointing|
| 1b-V/H             | 2011 Mar 21| 115/103                                       | 28.9                       | Pointing|
| 2a-V/H             | 2012 Mar 21| 108/95                                        | -30.3                      | Pointing|
| 2b-V/H             | 2012 Mar 21| 134/117                                       | 37.0                       | Pointing|
| 3a-V/H             | 2012 Apr 18| 94/81                                         | 19.2                       | Pointing|
| 3b-V/H             | 2012 Apr 18| 136/118                                       | 34.9                       | Pointing|
Appendix B: Herschel/HIFI Maps of 621 GHz Water Maser

Fig. B.1. Map of 621 GHz emission corresponding to dataset 2-H in Table A.1. The offsets from (R.A.[J2000]= 05h35m 14.3, decl.[J2000]= −05°22′33.7″) are given in the upper left of each panel in seconds of arc. The horizontal and vertical axes bordering the entire set of 15 panels correspond roughly to these respective offsets for the positions at which the spectra shown in the individual panels were observed. The fine vertical scales on the individual panels, run from [−0.2 to 2.5] degrees Kelvin; the width of the individual panels cover a $V_{\text{lsr}}$ range of [−60 to 80] km s$^{-1}$ roughly centered on the vertical red line marking $V_{\text{lsr}} = 12$ km s$^{-1}$, the velocity of the narrow 621 GHz maser feature.

Appendix C: Discussion on Pointing Errors

The source for the variability of the broad pedestal component in the 621 GHz spectral line requires explanation. More precisely, we need to determine whether some time-varying physical mechanism and/or pointing errors are responsible for the change that occurs in the pedestal between 2011 to 2012.

As the first and last set of observations involved a small map, we examined two possibilities. First, whether the increase in emission from the broad component is common to all areas of the map, and second, if not, whether there is a noticeable offset in the spatial positioning. Figures B.1 and B.2 illustrate the horizontally polarised versions of the two small maps taken during the first and last epochs of our observations. In Table A.1, this corresponds to observation numbers 2-H and 6b-H, respectively. From 2011 and 2012, the intensity of the maser line itself seems to systematically decrease between the maps of Figures B.1 and B.2. At the same time, in many panels toward the map center, the aforementioned broad component appears to get stronger. This trend differs at points farther from the center, where there is more of a decrease, especially in the line wings of the bottom left panels. This latter point seems to indicate systematic changes in the source. However, one possible explanation for the increase in the broad component may be due to the proximity of the Orion “hot core” (HC) whose molecular line emissions were studied extensively by Beuther et al. (2005). The HC is located at (R.A.[J2000]= 05h35m 14.50, decl.[J2000]= −05°22′30′.45) only about 6 arcseconds removed from Orion KL. It is displaced from our pointing direction by only 20″ in Right Ascension and 30″ in Declination, and thus lies at an offset of only 36 seconds of arc from our prime pointing direction. This small offset, barely exceeding the FWHM of our beam at 621 GHz, implies that even a relatively small error in pointing could effect a large apparent variability, given that the HC would lie on the flank of our beam profile.

In Section 3.2, we stated that the adjustment in the absolute pointing error (APE) improved the pointing accuracy of HIFI but retained some of its uncertainty. This is especially true of the mapped observations, which have additional pointing uncertainties due to relative offsetting and jitter, that may total 1′.5-2′.5 for OTF maps. Both mapping and pointed modes can be further misdirected from their intended pointing during telescope switching from OFF to ON source. Indeed the APE was verified during Herschel photometric operation and was never proven to exactly match while in spectroscopic observations. In general, HIFI has shown itself able to resolve source structure to better than 1″ at
its high-frequency end. Nevertheless pointing errors of order 3″
have occasionally been observed on Herschel.

As we are combining data across several Observation Days,
it is easy to conceive of pointing errors of this order. Together
with the large source gradient shown in Figures B.1 and B.2 and
the presence of the HC in the vicinity of our source, the effect of
pointing errors must be considered a likely source of variability
in the broad spectral component. Quantitatively, if one is to look
more closely at, for example, Figure B.2 there is a drastic, ~ 1.5
K increase in the broad component as one moves 12″5 from the
center position to that directly beneath. Following the discussion
from above, a reasonable pointing error of 3″, or 23% of the
map step size, would thus correspond to an increase of ~ 0.35
K in the broad pedestal. An offset of this magnitude from the
center position would therefore result in the amplitude of the
broad component rising to ~ 0.85 K, or ~ 1.7 times the intensity.