The hydroxyl satellite-line ‘flip’ as a tracer of expanding H\textsc{ii} regions

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ABSTRACT
Observations of the $^2\Pi_{3/2, J=3/2}$ ground state transitions of the hydroxyl radical (OH) have emerged as an effective tracer of ‘CO-dark’ molecular gas in diffuse regions of the Galactic interstellar medium (ISM). The transitions at 1612 and 1720 MHz in particular – the ‘satellite lines’ – are sensitive tracers of local environmental conditions. As a powerful example of the utility of the satellite-line transitions we discuss a peculiar spectral feature known as the satellite-line ‘flip’ wherein the satellite lines flip – one from emission to absorption and the other the reverse – across a closely blended double feature. We highlight 31 examples of the satellite-line flip from the literature and from previously unpublished data sets, 28 of which exhibit the same orientation with respect to velocity: the 1720 MHz line is inverted at more negative velocities, flipping to 1612 MHz inversion at more positive velocities. To explain these trends we propose a scenario where the alternating inversion seen in the flip arises from molecular gas both just inside and just outside a shock front surrounding an expanding H\textsc{ii} region: the H\textsc{ii} region provides the background continuum and its expansion accounts for the bias in velocity. We find that the flip can be reproduced across a wide range of number densities ($10^2 - 10^5$ cm$^{-3}$), a wide but high range of molecular gas temperatures ($50 - 150$ K), and requires moderate velocity dispersions (<3 km s$^{-1}$) and column densities alternately above and below approximately $10^{15}$ cm$^{-2}$.

Key words: Galaxy: disc – ISM: general – radio lines: ISM – ISM: H\textsc{ii} regions

1 INTRODUCTION
Molecular hydrogen in the interstellar medium (ISM) does not have readily accessible excited states throughout much of the temperature and density regimes in which it is expected to be found. Therefore, H$_2$ is generally observed via alternative molecular tracers, most common of which are the lower rotational transitions of carbon monoxide, particularly the CO ($J=1 \rightarrow 0$) transition. In low extinction regions of more diffuse molecular gas, CO is expected to dissociate in environments that still maintain H$_2$ (e.g. van Dishoeck & Black 1986; de Vries et al. 1987; Blitz et al. 1990; Wolfire et al. 2010), thus limiting its efficacy as a molecular gas tracer in these regimes. This ‘CO-dark’ gas has been shown to comprise a significant portion of the mass of molecular clouds (e.g. Reach et al. 1994; Grenier et al. 2005; Planck Collaboration et al. 2011). Indeed, the proportion of the mass of a molecular cloud that is CO-dark is roughly inversely proportional to its total mass (Grenier et al. 2005; Remy et al. 2018). This limitation of CO is therefore even more significant in the diffuse interstellar medium where up to 50% of the total mass may be missed. Hence we often turn to other tracers expected to better maintain their relationship with H$_2$ across these regimes: one such example is the hydroxyl radical, OH (Wannier et al. 1993; Liszt & Lucas 1996; Barriault et al. 2010; Allen et al. 2012, 2015; Li et al. 2018). The four $^2\Pi_{3/2, J=3/2}$ ground state transitions of OH occur at 1612.231, 1665.402, 1667.359 and 1720.530 MHz. These transitions are generally weak, and therefore are most readily observed in absorption against bright background continuum emission.

The OH in the diffuse molecular ISM is generally not in local thermodynamic equilibrium (LTE). In particular, the ‘satellite’ lines at 1612 and 1720 MHz almost always exhibit excitation not consistent with LTE (Elitzur 1992). Thus when considering the diffuse molecular ISM, studies often focus on the stronger ‘main’ lines at 1665 and 1667 MHz as their excitation is less likely to deviate significantly from LTE (e.g. Baud & Wouterloot 1980; Barriault et al. 2010; Nguyen et al. 2018; Li et al. 2018). In such cases reasonable assumptions may be applied to the excitation of the...
main lines and properties of the gas can be inferred without solving for the excitation of the entire OH ground state (e.g. Barriault et al. 2010; Rugel et al. 2018).

Our aim in this work is to demonstrate that the complexity of OH satellite-line excitation is an advantage, as its sensitivity to local environmental conditions carries with it information about that environment that may not be captured by the main lines. We demonstrate this through an illustrative example known as the satellite-line ‘flip’: a peculiar OH profile shape first described by Caswell & Haynes (1975), with examples seen in the literature as early as 1967 (Goss 1967). A typical example of the profile is given in Fig. 1. On one side of the feature the 1612 MHz line is seen in absorption while the 1720 MHz is in emission. The lines then flip their relative orientation to have the 1612 MHz line in emission and the 1720 MHz line in absorption, all within a closely blended double feature. Meanwhile, both main lines are in absorption, often obscuring the fact that two velocity components exist.

As we discuss in detail in Section 2, Elitzur (1976) showed that for a wide range of gas parameters, the satellite lines will flip (from 1720 MHz inversion to 1612 MHz inversion) as \( N_{\text{OH}}/\Delta V \) is increased past a value of approximately \( 10^{15} \text{cm}^{-2} \text{km}^{-1} \text{s} \). van Langevelde et al. (1995) carried out non-LTE excitation calculations to confirm the findings of Elitzur (1976) in the context of an extragalactic example of the flip towards Cent A. They tested a range of number densities, column densities, gas temperatures and radiation fields, and found that in models where a flip could be achieved, it did indeed occur at \( N_{\text{OH}}/\Delta V \approx 10^{15} \text{cm}^{-2} \text{km}^{-1} \text{s} \). Frayer et al. (1998) applied this same reasoning to another extragalactic example of the flip towards NGC 253. They interpreted the flip as an indication that \( N_{\text{OH}}/\Delta V \approx 10^{15} \text{cm}^{-2} \text{km}^{-1} \text{s} \), and \( N_{\text{H}} \approx 10^{22} \text{cm}^{-2} \), assuming \( \Delta V \approx 1 \text{km} \text{s}^{-1} \) in the region of 1720 MHz inversion. This is consistent with the value of \( N_{\text{H}} \approx 3 \times 10^{22} \text{cm}^{-2} \) found by Canzian et al. (1988) for this same region from observations of CO. Other than these two works, who attribute the satellite-line flip to a gradient in \( N_{\text{OH}}/\Delta V \), no local astrophysical process has been proposed to account for these observations.

In this work we identify, from our own observations and from the literature, 31 examples of the satellite-line flip (Goss 1967; Caswell & Robinson 1974; Caswell & Haynes 1975; Turner 1979; van Langevelde et al. 1995; Frayer et al. 1998; Brooks & Whiteoak 2001; Dawson et al. 2014; Rugel et al. 2018, Ogbodo et al. 2019, submitted) presented in Table 1. With the exception of the extragalactic examples described by van Langevelde et al. (1995) and Frayer et al. (1998), all are within our Galaxy. With only three exceptions, all of these examples are observations of OH gas towards bright background continuum sources, suggesting that the observed emission is stimulated emission with negative optical depth \( \tau \) (or equivalently, negative excitation temperature \( T_{\text{ex}} \)).

In this work we note the hitherto unnoticed fact that – with the same three exceptions – all exhibit the same orientation in velocity: the 1720 MHz inversion is seen at more negative velocities and the 1612 MHz inversion at more positive velocities.

This remarkable trend leads us to propose a physical model for the satellite-line flip where an expanding HII region provides the background continuum and the biased velocity field, stimulating 1720 MHz emission in the molecular gas just behind the shock front, and 1612 MHz emission just ahead of that shock front. To justify this model we first outline the key factors affecting OH excitation in the context of the satellite-line flip in Section 2. We then outline our physical model in detail in Section 3. We discuss the implications and limitations of this model in Section 4 and in Section 5 we conclude.

2 OH SATELLITE-LINE EXCITATION

In this section we outline the level population requirements for satellite-line inversion as seen in the satellite-line flip, and the de-excitation pathways that lead to these populations (Elitzur et al. 1976; Guibert et al. 1978). We then discuss the environmental conditions that influence the relative dominance of these de-excitation pathways, and how these could manifest in the observed satellite-line flip. A more exhaustive discussion of this subject can be seen in Elitzur (1992).

The \( ^2 \text{H}_2 \text{I}_J \), \( J = 3/2 \) ground rotational state is split into four levels via \( \Lambda \)-doubling and hyperfine splitting. These levels, as well as their allowed transitions at 1612, 1665, 1667 and 1720 MHz are illustrated in Fig. 2. Due to the different degeneracies of its upper and lower levels, inversion in the 1612 MHz line is achieved when the population of its upper level is greater than 3/5 that of its lower level. Inversion of

![Figure 1. Optical depth observations of hydroxyl made with the Australia Telescope Compact Array towards the bright background continuum source G340.79-1.02 from Petzler et al. (2019b, in prep.) as an illustrative example of the OH satellite-line flip. The 1612 MHz line can be seen in absorption at more negative velocities, transitioning to stimulated emission at -28 km s\(^{-1}\). The 1720 MHz line shows the opposite behaviour with stimulated emission at more negative velocities, transitioning to absorption at -28 km s\(^{-1}\). Both main lines (1665 and 1667 MHz) are in absorption but clearly indicate the presence of two blended velocity components, with peaks roughly corresponding to the peak emission in each satellite line. A radio-recombination line is detected toward this source, centred at -25 km s\(^{-1}\) (dotted line), indicating the presence of an HII region.](image-url)
the 1720 MHz line is achieved when the population of its upper level is greater than 5/3 that of its lower level.

The relative population of the OH ground state hyperfine levels in the ISM is largely determined by cascade pathways into the ground state from previously-excited higher rotational states. As all cascades into the ground state will pass through either the first excited \( ^1\Pi_{1/2} \), \( J = 5/2 \) or the second excited \( ^3\Pi_{1/2} \), \( J = 1/2 \) rotational state (Elitzur 1992), only these are illustrated in Fig. 3. Also illustrated in Fig. 3 are the allowed transitions (determined by the quantum mechanical selection rules) from the levels within those excited rotational states into the levels of the ground state. If the radiative decay pathways from the first and second excited rotational states into the ground state are optically thick, then the rates of the individual transitions within each pathway are independent of line strength, and depend only on the number of these pathways into the ground state (Elitzur 1976).

As illustrated in Fig. 2, the main-line transitions occur between upper and lower levels with the same angular momentum quantum number \( F \), while the satellite-line transitions occur between levels with different \( F \) number. This, along with the \( F \) numbers of the levels of the excited rotational states, introduces an asymmetry in the possible cascade pathways into the ground state for the satellite lines but not for the main lines; there are more allowed transition pathways from the first excited \( ^3\Pi_{1/2} \), \( J = 5/2 \) state into the upper level of the 1720 MHz transition than there are pathways into its lower level. Similarly, there are more allowed transition pathways from the second excited \( ^3\Pi_{1/2} \), \( J = 1/2 \) state into the upper level of the 1612 MHz transition than there are pathways into its lower level. Environmental factors that preference cascade pathways through the

| \( l^* \) | \( b^{*a} \) | \( v \) (km s\(^{-1}\))\(^b\) | 1612 MHz blue | 1720 MHz blue | Units\(^c\) | \( \theta^{d/2}_i \) | H\(\alpha\) assoc.\(^e\) | Y/N | Ref.\(^f\) |
|---|---|---|---|---|---|---|---|---|---|
| 8.10 | 0.20 | 13 | 17.8 | -0.15 | 0.11 | 0.25 | -0.37 | K | 18.8 | Y | A |
| 12.80 | -0.20 | 32.5 | 38.5 | -0.2 | 0.4 | 0.64 | -0.3 | Jy | 0.12\(^*\) | Y | B |
| 14.00 | -0.60 | 17.8 | 22.9 | -0.25 | 0.13 | 0.14 | -0.22 | K | 18.8 | Y | A |
| 19.08 | -0.29 | 62 | 71 | -10 | 10 | 10 | -15 | K\(^*\) | 0.77\(^*\) | Y | C |
| 19.61 | -0.23 | 43.9 | 48.2 | -0.32 | 0.1 | 0.56 | -0.15 | Jy | 0.12\(^*\) | Y | B |
| 30.50 | 0.00 | 90 | 95.2 | -0.52 | 0.34 | 0.18 | -0.34 | K | 18.8 | Y | A |
| 30.78 | -0.14 | 90 | 95 | -1 | 0.3 | 0.6 | -0.9 | K | 31.4 | Y | D |
| 32.80 | 0.19 | 7 | 20 | -15 | 15 | 70 | -60 | K\(^*\) | 0.77\(^*\) | Y | C |
| 34.25 | 0.14 | 60 | 63 | -0.21 | 0.02 | 0.2 | -0.03 | K | 18.8 | Y | E |
| 35.20 | -1.70 | 39.8 | 43.9 | -0.18 | 0.19 | 0.28 | -0.36 | K | 18.8 | Y | A |
| 48.92 | -0.28 | 5.6 | 6.5 | -0.165 | 0.029 | 0.127 | -0.104 | K | 0.77\(^*\) | Y | C |
| 49.37 | -0.30 | 63 | 66 | -90 | 100 | 90 | -80 | K\(^*\) | 0.77\(^*\) | Y | C |

Table 1. Locations of spectra exhibiting the satellite-line flip: where the conjugate relationship between the satellite lines flips across a closely-blended double feature. \(^a\)Locations of each flip are given in Galactic coordinates. \(^b\)The velocities of the more blue-shifted component and the more red-shifted component are given along with the peak values measured at 1612 and 1720 MHz. As these examples are drawn from disparate publications, the values of these peaks are approximate and their units of measurement (\(\tau\)) vary: continuum subtracted brightness temperature \(K\), \(\tau\) converted from Jy beam\(^{-1}\), continuum subtracted flux density \(Jy\), and optical depth \(\tau\). In all cases a positive value indicates relative emission and a negative value indicates relative absorption. \(^d\)The resolution of the flip observation is given in arcmin, and interferometric observations are indicated (\(*\)). \(^e\)The presence or absence of an associated \(H\alpha\) region is indicated.

\(^f\)References: (A) Turner (1979), (B) Ogbedo et al. (2019, submitted) (C) Rugel et al. (2018), (D) Goss (1967), (E) Petzler et al. (2019a in prep), (F) Xu et al. (2016), (G) Ebisawa et al. (2019), (H) van Langevelde et al. (1995), (I) Manchester et al. (1970), (J) Frayer et al. (1998), (K) Caswell & Robinson (1974), (L) Cunningham M.R. (private communication), (M) Dawson et al. (2014), (N) Petzler et al. (2019b in prep), (O) Brooks & Whiteoak (2001).
Second, in cool environments ($T \lesssim 50$ K) dominated by collisions, it can be energetically possible to excite transitions into the $^2\Pi_{1/2}, J = 5/2$ state with negligible excitation into higher states. In this case the cascade pathway via $^2\Pi_{1/2}, J = 1/2$ is removed, leaving the pathway via the $^2\Pi_{3/2}, J = 5/2$ state to dominate the population of the ground state levels (Elitzur et al. 1976). This pathway will in effect transfer molecules from the $F = 1$ levels of the ground state to the $F = 2$ levels, leading to sub-thermal excitation in the 1612 MHz line and inversion of the 1720 MHz line.

Third, the 1612 MHz pumping mechanism can be deactivated in regions of low OH column, allowing the 1720 MHz line to invert even in the case where both the first and second excited rotational levels are populated. The line strengths for transitions to the ground state from the second excited rotational state are about an order of magnitude lower than those from the first excited rotational state. As a consequence, for $10^{14} \lesssim N_{\text{OH}}/\Delta V \lesssim 10^{15}$ cm$^{-2}$ km$^{-1}$ s$^{-1}$ (Elitzur 1976; van Langevelde et al. 1995), transitions from the second excited rotational level are optically thin while transitions from the first excited level are optically thick. In this case, the rate of transitions from the second excited state to the ground state will be determined by their individual line strengths, which will tend to maintain the original population of the ground state levels. This prevents the transfer of molecules from the $F = 2$ levels of the ground state to the $F = 1$ levels, thus disabling the 1612 MHz pumping mechanism (Elitzur 1976). We believe that the satellite-line flip is caused by this third mechanism as we will now discuss.

### 3 PHYSICAL EXPLANATION OF THE FLIP

We propose a physical explanation for the satellite-line flip where the 1720 MHz inversion occurs in a layer of molecular gas just behind a shock front, and where the 1612 MHz inversion occurs in an adjacent layer just ahead of that shock front. Both layers have sufficient thermal energy to populate the first and second excited rotational levels — and invert the 1612 MHz line — but the 1612 MHz pumping mechanism is ‘switched off’ by the low column density of the inner layer, allowing the inversion of the 1720 MHz line. Our reasoning and evidence are detailed in this section.

The satellite-line flip has two components separated in velocity, with median separations of 4.8 km s$^{-1}$, but ranging from 0.7–40 km s$^{-1}$. This range is skewed by a single outlier, an extragalactic example of the flip towards NGC 253 which likely represents several beam-averaged components. Omitting this example makes the range of separations 1–16.8 km s$^{-1}$. The flip is most commonly observed with the 1720 MHz line inverted at more negative velocities and the 1612 MHz line inverted at more positive velocities — 90% (28/31) of the examples shown in Table 1 show this orientation.

The separation in velocity suggests that the satellite line flip may be associated with a coherent velocity field, such as expansion and/or infall. The observation that most of the flips have the 1720 MHz inversion at more negative velocities implies a bias in the orientation of this velocity field with respect to the observer. Since examples of the flip are observed in all quadrants of the Milky Way, this bias is not due to the large-scale Galactic velocity field. Instead, we note that all of the flips that demonstrate this
velocity bias are also observed against bright background continuum $T_C$: when $T_C \gg T_{ex}$, only the foreground gas will contribute significantly to the observed brightness temperature. Therefore, if the source of background continuum was also the source of the velocity field, this could provide a natural explanation for the observed bias in the orientation of the flip – in principle, a physically-associated source of continuum (e.g. an HII region) could provide the necessary bright background continuum and drive expansion. This led us to consider whether there was evidence for a local association between the OH gas and the background continuum illuminating it.

All but one of the examples of the flip towards bright background continuum (27/28) coincide positionally on the sky with the location of a known HII region. A flip was considered to ‘coincide’ with an HII region if the half-power beam-width with which it was observed overlapped with the recorded radius of an HII region. In the case of the two extragalactic examples, specific HII regions are not resolved but both are associated with large molecular structures that contain HII regions (Hodge & Kennicutt 1983; Ulvestad & Antonucci 1991). Excluding the two extragalactic examples, all but one of the flips associated on the sky with specific HII regions (24/25) also have recorded radio recombination lines (RRL) within ±10 km s$^{-1}$ of one or other component of the flip. The associations of the velocity components of the flips with the RRL of on-sky overlapping HII regions are illustrated in Fig. 4. All HII data were obtained from the Wide-field Infrared Survey Explorer (WISE Anderson et al. 2014, 2015, 2018) and from the Southern HII Region Discovery Survey (SHRDS Wenger et al. 2019).

In the case of the 24 examples where the satellite-line flip shows the 1720 MHz inversion at more negative velocities, has a bright background source of continuum, and is associated on sky and in velocity with an HII region, we may consider a model in which an expanding HII region drives a shock into the molecular gas surrounding it, as illustrated by the cartoon in Fig. 5. For a moderate shock velocity ($< 20$ km s$^{-1}$), H$_2$ is only partially dissociated, leaving a significant amount of molecular gas behind the shock (Draine et al. 1983; Flower et al. 2003), which may potentially experience quite a different set of environmental conditions to the rest of the cloud. The velocity discontinuity at the shock means that the molecular gas inside and outside the shock front now have different line-of-sight velocities, providing a natural explanation for the velocity components of the flip. As previously mentioned, all but one of the flips have velocity separations consistent with the required low-velocity shock. In this picture, the molecular gas just behind (i.e. inside) the shock hosts the 1720 MHz inversion, while the gas just in front (i.e. outside) of the shock hosts the 1612 MHz inversion.

With reference to the mechanisms of satellite-line inversion outlined in Section 2, it seems unlikely that the 1720 MHz inversion behind the shock indicates an environment where excitation into the second excited rotational state is prevented due to lack of available FIR photons, as this gas would be heated by the HII region (e.g. Tielens & Hollenbach 1985; Hollenbach & Tielens 1999). This is supported by the 1D hydrodynamical and chemical modelling of Hosokawa & Inutsuka (2006), who modelled the expansion of ionisation and dissociation fronts around an HII region generated by a single massive star. They found that the molecular gas inside the shock is substantially heated ($\approx 100-200$ K) as is the molecular gas just outside the shock ($\approx 50-100$ K); the first and second excited rotational states of OH are populated in both layers. Instead, in agreement with van Langevelde et al. (1995) and Frayer et al. (1998) we believe that the 1720 MHz inversion in the gas behind the shock is achieved by its lower column density.

The 1612 MHz inversion in the layer outside the shock requires $N_{OH}/D \gtrsim 10^{15}$ cm$^{-2}$ km$^{-1}$ s, while the gas just inside the shock requires $N_{OH}/D \lesssim 10^{15}$ cm$^{-2}$ km$^{-1}$ s to disable the 1612 MHz pumping mechanism and allow the 1720 MHz inversion. Assuming a characteristic molecular cloud number density of $n_{H_2} \approx 10^3$ cm$^{-3}$, a velocity dispersion of $\Delta V \approx 3$ km s$^{-1}$ (consistent with the observed linewidths of the components of the flips), and an OH-to-H$_2$ abundance ratio of $10^{-7}$ (e.g. Nguyen et al. 2018), this implies a line-of-sight thickness of $\gtrsim 10$ pc in order to allow 1612 MHz
inversion. If the host molecular cloud had a higher number density or if the abundance of OH relative to H$_2$ were enhanced, this line-of-sight thickness would reduce.

Assuming that the number density of molecular gas is elevated just inside the shock (n$_{H_2}$ $\approx$ 10$^6$ cm$^{-3}$), the line-of-sight extent of this region must not exceed 1 pc. Hosokawa & Inutsuka (2006) found that this region would be very thin ($\approx$ 0.1 pc) for a central ionising star of 19 M$_\odot$; the 1720 MHz line would be readily inverted in this gas.

We conducted molecular excitation modelling to explore these regions of parameter space in order to confirm that they could indeed give rise to the flip. We examined the effect on the flip of column density N$_{OH}$ and velocity dispersion $\Delta V$ as predicted by Elitzur (1976), and how these effects persisted across a range of gas temperatures T$_{gas}$, number densities n$_{H_2}$, dust temperatures T$_{dust}$ and visual extinctions A$_V$.

We use a non-LTE molecular excitation code to determine the line populations of the of the lowest 8 rotational states of OH and their hyperfine levels (32 levels in all). The code employs a large velocity gradient escape probability approach to radiative transfer in a uniform slab and includes line overlap. The energy levels and Einstein coefficients for the hyperfine transitions are taken from Destombes et al. (1977), while the infrared transitions and A coefficients are taken from Brown et al. (1982). Collisional rate coefficients with H$_2$ and helium are taken from Offer et al. (1994) and Klos et al. (2007) and are computed for electrons using the prescription from Chu (1976). The infrared radiation fields from dust lying outside the slab and within the slab are represented by grey body models using the MRN dust extinction curve of Draine & Lee (1984). The input parameters are gas temperature T$_{gas}$, velocity FWHM $\Delta V$, fraction of ortho-H$_2$, abundances of OH, He and e relative to H$_2$ (X$_{OH}$, X$_{He}$, X$_e$), external dust temperature T$_{dust}$ and visual extinction A$_V$, internal dust temperature T$_{dust}$, number density n$_{H_2}$ and column density N$_{OH}$. The fraction of ortho-H$_2$ (0.75), X$_{OH}$ (10$^{-7}$), X$_{He}$ (10$^{-4}$) and X$_e$ (10$^{-4}$) were held constant for all models.

The molecular gas behind and in front of the shock was modelled as two adjacent parallel slabs of uniform gas with a 3 km s$^{-1}$ offset in line-of-sight velocity, intended to be consistent with the instance of the flip towards G340.79-1.02 illustrated in Fig. 1. The placement of these slabs are shown in Fig. 5. The range of parameters tested are shown in Table 2. The choice of parameter ranges included ‘reasonable’ regions of parameter space consistent with expected conditions in the ISM and from the Hosokawa & Inutsuka (2006) models. These range from quiescent molecular gas to that nearing dissociation near an H$\alpha$ region. The results of our modelling are illustrated in Fig. 6.

Fig. 6 shows optical depth of the 1612 and 1720 MHz OH transitions. Pink regions indicate inversion of the 1612 MHz line and blue regions indicate inversion of the 1720 MHz line. The individual panels in Fig. 6 show how the optical depths of the satellite lines vary with velocity dispersion $\Delta V$ and column density log N$_{OH}$. There is a clear separation between regions of 1720 MHz inversion and 1612 MHz inversion that persists from panel to panel as number density and gas temperature are varied. This is consistent with the known ‘conjugate’ behaviour of the satellite lines (Elitzur 1976; van Langevelde et al. 1995), and demonstrates that the existence of the satellite-line flip is most sensitive to column density and velocity dispersion. (Note that these results were largely insensitive to variations in visual extinction and dust temperature.) At T$_{gas}$ = 30 K only the 1720 MHz line was inverted, and at lower gas temperatures neither line was inverted. We comment on the implications of this in Section 4.

A synthetic profile corresponding to the regions of parameter space indicated by the blue and red stars in Fig. 6 is shown in Fig. 7. This synthetic profile is generated from our molecular excitation code and represents the two adjacent parallel slabs of molecular gas illustrated in Fig. 5. The parameters of the two slabs are given on the figure. This synthetic profile is broadly consistent with observed instances of the flip: all examples of the flip in the literature have both main lines in absorption, generally with stronger absorption.

Table 2. Properties of models explored using our molecular excitation code to approximate slabs of gas internal and external to a shock front surrounding an H$\alpha$ region as illustrated in Fig. 5. The effects of gas temperature, velocity dispersion, OH column density and H$_2$ number density on the satellite-line flip were explored across the region of parameter space indicated by the ranges given. Values of ortho : total H$_2$ ratio (0.75), OH, He and e$^-$ abundances relative to H$_2$ (10$^{-7}$, 10$^{-1}$ and 10$^{-4}$, respectively) were kept constant. The resulting optical depths at 1612 and 1720 MHz found from this modelling are illustrated in Fig. 6.
than the satellite lines, and often stronger absorption in the more positive velocity component.

4 DISCUSSION

The structure of HII regions and their surrounding clouds is generally much more complex than described by our model (or, indeed the models of Hosokawa & Inutsuka 2006). However, it is instructive to begin by considering such simple 1D models to investigate their plausibility before examining more realistic scenarios. In fact, all we require to achieve the OH satellite-line flip is molecular gas on either side of a velocity discontinuity with sufficient temperature and column densities to invert the appropriate lines. The physical model of a shock surrounding an expanding HII region as described in Section 3 is consistent with at least 24 examples of the satellite-line flip, but a more general model of a low-velocity shock is potentially consistent with all 31 examples.

The most important aspect of the physical explanation of the flip we propose is the presence of molecular gas on either side of a velocity discontinuity or gradient, with the gas on one side having \( \Delta V_{\text{OH}} \gtrsim 10^{15} \text{cm}^{-2} \text{km}^{-1} \text{s}^{-1} \) and the other side \( \Delta V_{\text{OH}} \lesssim 10^{15} \text{cm}^{-2} \text{km}^{-1} \text{s} \). In addition to the shocks surrounding HII regions, such velocity discontinuities or gradients could be caused by other bulk movements such as colliding streams or distant supernova remnants. In the absence of a central driving continuum source (against which only the foreground component will dominate), a flip produced by such a mechanism would be expected to have random orientation with respect to the observer. Indeed, 3/5 of the observed instances of the flip with no HII association have the 1612 MHz line inverted at more negative velocities. We also note that while the sample size is small, these examples of the flip not associated with HII regions tend towards lower mean velocity separations (2.2 km s\(^{-1}\)) than those with HII associations (5.7 km s\(^{-1}\)) when excluding the outlying flip G277.81+32.42 towards NGC 253). This suggests that the velocity separation of these examples may be caused by a lower-velocity shock than in the HII regions in the other examples.

We speculate that the flips towards G048.92-0.28 (Petzler et al. 2019a in prep) and G36.95-0.20 (−40 km s\(^{-1}\), Dawson et al. 2014), which both have the 1720 MHz line inverted at more negative velocities but do not have associated HII regions, may represent shocks moving towards the observer. On the other hand, evidence suggests that the flips toward G172.80-13.24 (Xu et al. 2016) and G173.40-13.26 (Ebisawa et al. 2019) and G175.83-9.36 (Petzler et al. 2019a in prep) – which all have the 1612 MHz line inverted at more negative velocities and also do not have associated HII regions – represent shocks moving away from the observer. The flips towards G172.80-13.24, G173.40-13.26 and G175.83-9.36 are all part of the Taurus molecular cloud complex: (Xu et al. 2016) suggested the presence of a C-shock caused by colliding streams or gas flows in the region of G172.80-13.24, and Ebisawa et al. (2019) suggest the presence of a mass of low column density molecular gas (\( N_{\text{OH}} \approx 10^{15} \text{cm}^{-2} \)) moving away from the observer, colliding with and compressing a cooler region with sub-thermally excited 1720 MHz and 1612 emission in the region of G173.40-13.26. These observations...
are highly consistent with our proposed physical explanation of the satellite-line flip.

This picture of shocks without an associated Hii region then leads to the question of how such gas would be heated: our modelling (see Fig. 6) implied at least 50 K was required to invert the 1612 MHz line, and that ~30 K was required to invert the 1720 MHz line. Our physical explanation of the flip relied on collisions to populate the excited rotational levels of OH, but this population could also be achieved with FIR photons from warm dust. We find that the satellite-line flip can also be achieved at lower gas temperatures ($T_{\text{gas}} \approx 20$ K) in models with high external dust temperature ($T_{\text{dust}} \gtrsim 60$ K) and/or high dust column densities ($A_v \gtrsim 29$ mag). Ebisawa et al. (2019) recently presented similar non-LTE excitation modelling of the flip towards G173.40-13.26 in Taurus using a high dust column density ($A_v \approx 150$ mag). This allowed them to successfully model the observed sub-thermal excitation of the 1720 MHz line responsible for the absorption against the CMB. However, it is unclear if such a high dust column could reasonably exist in a structure such as Taurus, perhaps indicating that the gas is indeed heated to $T_{\text{gas}} \approx 50$ K.

It is interesting to note in the context of our aim to illustrate the advantage afforded by the complexity of the satellite lines, that it was the observed sub-thermal excitation of the 1720 MHz line that prompted Ebisawa et al. (2019) to implement an updated dust spectrum. Their previous models were not able to account for this sub-thermal excitation, which would not have been noticed had they focused only on the main lines.

Our physical explanation of the flip could be supported by follow-up observations. For example, high resolution observations of examples of the flip that are known to correspond in position and velocity to Hii regions would allow further constraints to be placed on the physical dimensions and orientations of the molecular gas.

5 CONCLUSIONS

In this work we present 31 examples from the literature of the OH satellite-line flip: a peculiar profile wherein both satellite lines flip – one from emission to absorption and the other the reverse – across a closely blended double feature. We present an explanation of the consistent velocity orientation of this profile as two adjacent layers of molecular gas on either side of a shock wave expanding outwards from an ionised region. We support this claim through a molecular excitation model of these adjacent layers, showing that the observed profile can be replicated across a wide range of number densities and gas temperatures if those layers possess a $N(\text{OH})/\Delta V$ gradient crossing $N(\text{OH})/\Delta V = 10^{15}$ cm$^{-2}$ km$^{-1}$ s. We conclude therefore that the satellite-line flip can trace such $N(\text{OH})/\Delta V$ boundaries surrounding expanding ionised gas. The velocity separation of the components of the flip can then inform the kinematics of the associated shock, thus informing molecular excitation and hydrodynamical modelling. This work highlights the sensitivity of the satellite lines to local column and velocity dispersion, and therefore the benefits of observing these oft-neglected lines.

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