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A review about the alleged role of the hydroxyl OH absorption in the decimetric spectrum of the solar active regions as observed by RATAN-600

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Abstract Earlier solar radio observations at RATAN-600 solar facility regarding the solar active regions with overhanging chromospheric filaments occulting partly or wholly the active regions have shown that there is a depression like phenomenon in the decimetric radio spectrum. In order to explain this phenomenon, it was proposed that this was actually caused due to the absorption by the hydroxyl i.e., OH radical, which should be present in the filaments due to their relatively cool temperature, which ranges from around 4000°K to 20000°K. However, in our work we show that there are many flaws in the interpretation based on such a molecular absorption and show that the observed effect cannot be due to such an absorption.

Keywords: radio waves; molecular absorption; chromospheric filaments; solar activity

1. Introduction

The Sun is the magnificent natural source for the various exotic plasma phenomena, which manifest themselves in different wavelengths of the electromagnetic radiation. The study of these phenomena has both practical as well as theoretical interests and therefore our Sun is regularly observed using different telescopes both ground based and space borne in wavelengths spanning from the gamma rays to the long wavelength radio waves. One such telescope which has some of the unique observational capabilities is RATAN-600 with its solar spectral polarization complex (SSPC), that regularly scans the Sun in the decimetric (1-3 GHz) and centimetric (3-18 GHz) radio spectra both in transit and tracking modes. RATAN-600:SSPC was retrofitted with a new decimetric complex that

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possesses very high spectral resolution of about 4 MHz and has the potential of getting even higher just by a software reconfiguration or upgrade Ripak et al. (2023). Although, the scans are one dimensional the ability to scan the Sun at such a high spectral resolution and the relatively large surface area of the radio antenna can give important information of the spectral fine structure of the upper chromosphere and corona. The regular observations made by RATAN-600:SSPC in the decimetric radio spectrum corresponding to the solar active regions with overhanging chromospheric filaments, revealed that there are depressions or dips in the observed flux in the spectral domain ranging from 1 GHz to 3 GHz with some prominent depressions mainly seen in the narrow window spanning from 1.4 GHz to 1.7 GHz. This was first demonstrated in Ovchinnikova, Bogod, and Lebedev (2024), where it was suggested that this is caused due to the spectral microwave absorption corresponding to the hyperfine splitting of the frequencies in the ground state $X^2\Pi_{3/2}$ of the hydroxyl i.e., OH radical. This idea was corroborated by theoretical calculations using the data provided by the HITRAN database Gordon et al. (2026) about the molecular spectra of the OH radical.

In what follows, we closely analyze the important theoretical and experimental aspects of Ovchinnikova, Bogod, and Lebedev (2024) by considering the same parameters for temperature and other physical quantities related to the filaments that were used there and conclusively show that there are fundamental flaws in it as well as prove that this phenomenon couldn't have been due to the absorption by the OH radical or for that matter due to any other molecular entity from the HITRAN database that includes almost all the prominent molecular types relevant to the astrophysical context.

2. The flaws in the interpretation in terms of the OH radical's decimetric absorption

First let us start with the explanation for the observed dip in terms of the absorption due to the OH radical in the solar filaments that are in the vicinity of an active region. It is claimed that the OH radical's transition corresponding to the frequency $\sim$1650 MHz is responsible for this effect. The cold filament that protrudes on and above the active region supposedly absorbs this frequency leading to the reduction of the energy corresponding to this frequency. Now the data showing this dip in the decimetric radio spectrum clearly shows that the width is definitely of the order of $\sim$10 MHz. This is especially interesting as we know that the reasons for the broadening of the spectral emission or absorption lines are as follows:

1. Thermal Doppler broadening
2. Turbulence
3. Stochastic Stark effect (Very important in proton rich environment like solar corona)
4. Pressure induced broadening due to the stochastic Van der Waals interactions.
5. Ordered motion such as rotation or vorticity of the medium which as a whole is observed as a point object.
6. Possible data processing artifact which can cause broadening due to the

inadequate data.

Among the above-mentioned reasons, the most common are the thermal Doppler broadening and broadening due to the stochastic interactions. In Ovchinnikova, Bogod, and Lebedev (2024), the following algorithm derived from the HITRAN website (https://hitran.org/) for evaluating the absorption coefficient was used and one can find a very good discussion about this in the classic text on the essentials of the radio astronomy by Condon and Ransom Condon and Ransom (2016). For the sake of convenience we briefly summarize the steps involved here as follows:

1. Obtain the spectral line intensity $S_{ij}\left(T_{ref}\right)$ and the partition function $Q\left(T_{ref}\right)$ for the OH radical at the frequency $\nu_{ij} = 1650$ MHz and at the reference temperature $T_{ref} = 296$ K using the HITRAN database at https://hitran.org/. From hereon, the indices i and j in the subscript indicate the transition from the i^{th} to the j^{th} quantum state.

2. The obtained values are then used to evaluate the line transition intensity $S_{ij}\left(T\right)$ at a temperature of interest which in their case is $T = 5000°$ K. To do this the following formula (1) is used, by once again obtaining the value of $Q(T)$ from the HITRAN website:

$$S_{ij}\left(T\right) = S_{ij}\left(T_{ref}\right)\frac{Q\left(T_{ref}\right)}{Q\left(T\right)}\frac{e^{\frac{-h\nu_{ij}}{kT}}}{e^{\frac{-h\nu_{ij}}{kT_{ref}}}}\frac{1-e^{\frac{-h\nu_{ij}}{kT}}}{1-e^{\frac{-h\nu_{ij}}{kT_{ref}}}}, \tag{1}$$

here h, k are the Planck's and Boltzmann's constants respectively.

3. Later the line profile is considered either as a Gaussian, Lorentzian or a Voigt (convolution of a Gaussian and a Lorentzian) depending upon the situation under consideration. If the pressure is extremely feeble then the line profile was chosen as per the recommendation of the HITRAN site as a Gaussian line profile due to the thermal Doppler broadening. The half width at half maximum is then given by:

$$W\left(T\right) = \sqrt{\frac{2kTln\left(2\right)}{mc^2}}\nu_{ij}. \tag{2}$$

In the original HITRAN notation $\alpha_D\left(T\right)$ is used instead of $W\left(T\right)$. Now the line profile equation is given by:

$$f_G\left(\nu, \nu_{ij}, T\right) = \sqrt{\frac{ln\left(2\right)}{\pi W\left(T\right)^2}} \cdot e^{-\frac{\left(\nu_{ij}-\nu\right)^2 \cdot ln(2)}{W(T)^2}} \tag{3}$$

Therefore, this line profile is due to the thermal Doppler broadening and no stochastic Stark effect or pressure induced broadening or any other mechanism other than the thermal Doppler broadening are used. Now the absorption coefficient is calculated as follows:

$$k_{ij}\left(\nu, \nu_{ij}, T\right) = S_{ij}\left(T\right) \cdot f_G\left(\nu, \nu_{ij}, T\right). \tag{4}$$

The essence of this expression is that more the number of entities that are inclined towards the transition from the i^{th} to the j^{th} state, more is the absorption. That is if the line width is broad then, there are lesser favorable entities (OH radicals in this case) to undergo the transition. Similarly, the narrower the line width the greater the absorption.

Now let us look at the Doppler broadening due to the thermal motion which is given by the following expression: $\delta f = \sqrt{\frac{8kTln(2)}{mc^2}} f$, here we have, m the mass of the particle involved in the light matter interaction, f is the frequency of the spectral line, δf is the broadening of the frequency due to thermal Doppler broadening and T is the temperature of the medium with the rest of the constants k, c retaining their usual designations for the Boltzmann's constant and the speed of light in vacuum respectively. With this formula we can actually calculate the broadening of the OH radical's molecular spectral line at the frequency ∼1650 MHz and at the temperature $T = 5000°$ K. This gives us the frequency broadening as $\delta f \sim 30$ or 40 KHz, where as the observed broadening of the frequency at ∼1650 MHz by RATAN-600:SSPC is around ∼40 MHz which corresponds to the temperature $T \sim 1.22 \times 10^{9}$°K, i.e., temperature even hotter than the hottest parts of the corona and surely several orders of magnitude higher than the dissociation energy of the OH radical which is around the temperature of ∼40000°K and therefore leading to the obvious contradiction. At this point it is worth noting that the theoretically calculated broadening in Ovchinnikova, Bogod, and Lebedev (2024) is therefore around ∼ 40 KHz and not 40 MHz as attributed in that article after which it was falsely asserted that the theoretical line width of the absorption due to OH and the experimentally observed line width of the signal are of the same order of magnitude. This fact is of significant importance because, this aspect will be used by us later in our present work to conclusively prove that the signal cannot be due to the OH.

However, this broadening which is around 1000 times the thermal Doppler broadening is attributed to the Zeeman effect. This assertion has a logical flaw as the magnetic field changes the degeneracy of the states and one cannot use blindly the formulae with the values of degeneracy without the magnetic field. Also, as said any broadening be it due to the stochastic Stark effect or Zeeman effect or pressure induced broadening should be accounted in the calculation of the absorption coefficient. Here it is necessary to clarify that the HITRAN database in itself has no serious issues as this database only consists of the data about the various molecules for calculating the absorption coefficients and other important parameters that are relevant to the molecular spectroscopy tuned for the laboratory or atmospheric molecular gases which are usually not subjected to the magnetic fields as is the case with the solar coronal plasma. If one looks carefully at the formulae prescribed at the HITRAN web site, one immediately notices that the line profile function $f_L(\nu, \nu_{ij}, T)$ is inversely proportional to the half width at half maximum (HWHM) if the shape of the profile is taken constant. In other words, the real line profile can be expressed correct to the order of magnitude as follows:

$$f_L(\nu, \nu_{ij}, T) \sim \left(\frac{const}{HWHM}\right) \times \Phi(\nu_{ij}, \nu, T), \tag{5}$$

here $\Phi(\nu_{ij}, \nu, T)$ is the shape function of the actually observed line instead of some function such as Lorentzian or Gaussian used to fit the curve or profile of the spectral line. As the HWHM in the present case is around 10 MHz, the results corresponding to the absorption coefficient were exaggerated by 1000 times and thereby rendering the calculated absorption coefficient quite incorrect. Actually the fact that the observed HWHM is of the order of $\sim$ 10 MH rigorously indicates that the observed depression can neither be due to OH nor be due to any other molecular species from the catalog of HITRAN's molecular database. Here, the line broadening due to the inadequate data can be excluded because the RATAN 600:SSPC has a spectral resolution of 4 MHz Ripak et al. (2023) and the observed depression's line width is around $\sim$40 MHz, which usually translates to 5 data points and hence sufficient to estimate at least the order of magnitude of the depression with complete confidence.

Now the reason associated with the turbulence cannot be invoked to the extent needed because such an intense turbulence should have heated plasma considerably due to the motion of different layers of plasma against the internal friction. Also, the reason associated with the ordered motion can likewise be excluded due to its absence in the other data from telescopes such as Solar Dynamics Observatory (SDO), Hinode and etc.

Another important issue that that discredits the theoretical argument provided in Ovchinnikova, Bogod, and Lebedev (2024) in favor of the OH absorption is the use of a very primitive form of the Beer Lambert's law given by:

$$I = I_0 e^{-\alpha(\nu,T)u}, \tag{6}$$

here $\alpha(\nu, T)$ represents the coefficient of absorption, u is the column density and I-intensity at the exit from the filament. The problem with such an equation is that even if the overhanging filament is brighter than the active region, one still obtains an absorption as there is no term representing the emission due to the filament itself. The proper differential equation in the present context will be the radiative line transfer equation given by:

$$\frac{dI}{dx} = -\alpha(\nu, T) \cdot I + j(\nu, T). \tag{7}$$

Here $j(\nu, T)$ represents the emission due to the filament itself at a given frequency ν and temperature of the filament T. It can be easily noticed that once $j(\nu, T) = 0$ then the above equation gives the well-known laboratory relevant Beer Lambert's law. One must solve the above differential equation accounting for the inhomogeneous nature of the solar corona in general and the chromospheric filament in particular especially when we are concerned with the radio spectrum, as the Langmuir frequency of the surface plasma of the flux tubes which constitute the filament can easily fall in the domain of the radio frequency. In reality this is further complicated by the presence of the magnetic field at the active regions, which can seriously influence the intensity function I due to the cyclotron radiation which usually corresponds to the radio spectrum. However, the simple Beer Lambert law based calculation gives the upper most value for the spectral depression because $j(\nu, T) > 0$ always.

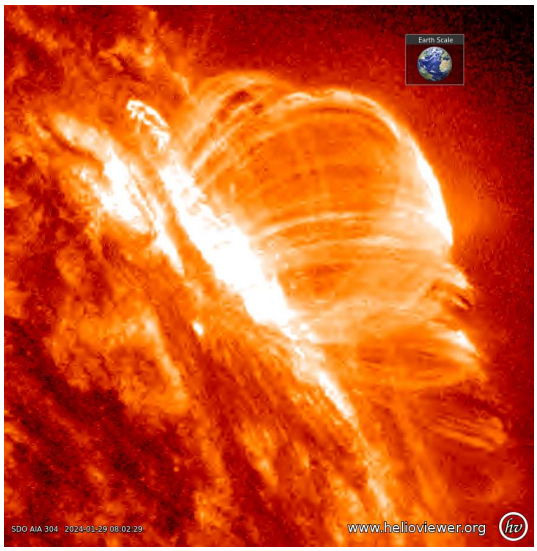


Figure 1. The almost immediate aftermath of the C5.6 class flare that took place on 29th Jan 2024 from 07:50 UT till 08:04 UT as seen in the 304 Å by the Solar Dynamics Observatory (SDO). This event was also observed by RATAN-600:SSPC and the data provided in Ovchinnikova, Bogod, and Lebedev (2024) clearly shows the depression like phenomenon in the decimetric radio spectrum.

It must also be stressed that the equilibrium between the unionized and ionized species of the OH radical that is the equilibrium between $OH \longleftrightarrow OH^+$ is not considered in Ovchinnikova, Bogod, and Lebedev (2024). This is crucial because OH^+ is more stable than OH as the dissociation energy of the OH^+ molecular ion is $\sim$5 eV, whereas the dissociation energy of the OH radical is $\sim$4 eV Sinha and Tripathi (1990). Therefore, a fraction of the produced OH should exist in the form of OH^+ molecular ion reducing the amount of OH available for the absorption. This is important because the concentration of OH appears as the exponent in the radiative line transfer equation and a small change in the concentration can give a relatively big change in the intensity.

There is also one other logical contradiction in Ovchinnikova, Bogod, and Lebedev (2024). If we look at the Figure. 2a of Ovchinnikova, Bogod, and Lebedev (2024) we see clearly that the active region is a flaring active region and the coronal arcade is glowing brilliantly in the 304 Å as shown here in Figure 1. In the same work it was asserted that the coronal rain which consists of relatively cool plasma had the required OH needed to show the observed depression. However we see that the coronal arcade which hosted the coronal rain was not in front of the solar disc but was against the open Sky background as a result of which we must actually observe more emission than absorption just as we observe the solar prominences as bright manifestations in the Hα line, when they appear at the solar limb in contrast to the case, when they are in the interior of the solar disc.

3. The proof that the observed signal is not due to OH radical's molecular absorption

We can now conclusively prove that the observed depression at RATAN-600:SSPC in the decimetric spectrum regarding the solar active regions with the overhanging filaments is not due to the OH radical's molecular absorption through the following logic. We use the estimates provided in Ovchinnikova, Bogod, and Lebedev (2024) about the upper limit of the available oxygen i.e., 8.8 Dex, that corresponds to the photospheric concentration of this element according to Bergemann et al. (2021) and attribute this concentration even to the chromospheric filament. We further assume that all the available oxygen is simply used up in the formation of the OH molecular radical giving rise to the maximum most concentration of OH, which actually should be higher than the real maximum concentration of this element in the filament as the chromosphere is considerably less dense than the photosphere. Now, if there are no line broadening mechanisms other than that due to the Heisenberg's uncertainty principle then the observed depression is the maximum most, but as soon as some line broadening mechanism gets involved such as the thermal Doppler broadening or stochastic Stark effect or etc., the width of the observed spectral line increases at the cost of the depth of the spectral absorption or emission line. This is because the number of molecular entities taking part in the transition process leading to the absorption or emission is constant. We use this logic to prove our point regarding the contribution of the OH absorption to the observed phenomenon at RATAN-600's solar observations. In what follows, we use the theoretical depression as calculated by Ovchinnikova, Bogod, and Lebedev (2024) due to the OH radical's absorption.

By considering that the only line broadening mechanism other than the quantum mechanical uncertainty principle is due to the thermal Doppler broadening and with the above consideration that the whole of the oxygen is used up leads to the line broadening of around $\sim$40 KHz and an upper limit for the depression of about $\sim$0.15%, which in terms of spectral flux density is of the order of $\sim$ 0.01 s.f.u. But this is barely more than the minimum most flux density that can be registered in the transit and the tracking modes by the RATAN-600's solar complex. However, in reality the observed flux's depression has a width of around $\sim$40 MHz i.e., the observed width is around 10^3 times the width that would have been had it been only due to the thermal Doppler broadening. If we now consider the additional broadening is due to the other widely known processes then it must reduce the depth of the depression by at least three orders of magnitude because the number of molecules is constant as earlier mentioned and the actual drop in the intensity should be even smaller than this estimate because of the the nonzero concentration of the ionized radical i.e., OH^+ and also due to the nonzero emission of the filament itself i.e., the term $j(\nu, T)$ in the radiative transfer equation given by Eq.7. However, such a reduction would completely deprive RATAN-600:SSPC from observing any such depression. The mere fact that we are able to consistently observe the signal with the given depth and width in the transit mode clearly signifies that the observed phenomenon couldn't have been due to the absorption by the OH radical's molecular transition. Otherwise,

we need three orders of magnitude more oxygen than is available in order to account for the observed depression with the same width, which would keep the oxygen and the hydrogen on the same footing as the concentration of the neutral hydrogen is around $\sim 10^{11}/cm^3$ in the chromospheric filaments. But this is experimentally not the case as the available oxygen is considerably less than hydrogen. Hence the proof that the observed phenomenon is not fundamentally due to the OH. This logic also applies to the other molecular species from the HITRAN database because the line intensities of the rest of the molecular species are less than that of the OH.

4. Conclusion

We have shown that the claim that the depression in the decimetric radio spectrum of the active regions with filaments is due to the absorption by OH is indeed incorrect. However, this is not to say that OH doesn't exist in the solar atmosphere as the existence of many simple molecules including OH was established a long time ago Pande, Gaur, and Tripathi (1969), but it is just that this molecule doesn't play a descisive role in the observed effect. It turns out that this cannot likewise be due to the microwave absorption of any other molecule from the HITRAN database, which includes almost all usually found molecules in the astrophysical atmospheres. The reason for the observed phenomenon according to the data obtained from the RATAN-600:SSPC should be something more subtle and demands more careful attention and we are going to address this issue in our upcoming work.

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