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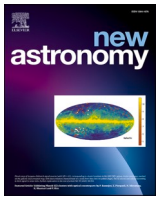

On the effective temperature of large sunspot umbra using AlH molecular lines

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ABSTRACT

In this work, the radiative transition parameters including Franck–Condon (FC) factors, r-centroids, electronic transition moment, Einstein coefficients, band strength, oscillator strength, lifetime and effective vibrational temperature have been computed for $A^1\Pi - X^1\Sigma^+$ and $C^1\Sigma^+ - A^1\Pi$ systems of aluminium monohydride (AlH) molecule by the numerical integration method for the experimentally known vibrational levels using Rydberg – Klein – Rees (RKR) potential. The computed radiative transition parameters are tabulated. A significant number of well resolved AlH molecular rotational lines of $A^1\Pi - X^1\Sigma^+$ (0,0), (1,1) and (0,1) bands are identified in the sunspot umbral spectrum and the estimated effective rotational temperature has been determined as 2315 K, 2155 K and 1838 K respectively. The effective vibrational temperatures of the $A^1\Pi - X^1\Sigma^+$ and $C^1\Sigma^+ - A^1\Pi$ systems are found to be 5682 K and 3472 K respectively. Hence, the radiative transition parameters and the effective temperatures confirm the presence of AlH molecule in sunspot spectra.

1. Introduction

Diatomic monohydride molecules are the first species to be identified in interstellar region. Aluminium monohydride (AlH) molecule is astrophysically important, because of its presence in the cosmic object spectra (Singh, 1988), in the atmospheres of M-, S-, Sp-, and C-type stars (Merrill, 1953) and in the emission spectra of sunspots (Sotirovski, 1972 and Narasimhamurthy et al., 1983). Also the diatomic aluminium based molecules (like AlO, AlF and AlC) had been identified in the sunspot umbral spectra (Sriramachandran et al., 2013; Bagare et al., 2006 and Sindhan et al., 2020) and in the star IRC+10,216 (Sindhan et al., 2020). The CaH molecular band systems identified in sunspot (Olmsted, 1908), M dwarfs (Eagle, 1909) and G-type stars (Campbel et al., 1984 and Barbuy et al., 1993). Engvold et al. (1980) identified the presence of CrH molecule in sunspot umbra and in the atmospheres of several S-type stars (Lindgren and Olofesson, 1980). Further, BeH and FeH molecules were identified in the sunspot spectra (Shanmugavel et al., 2008 and Mulchaey, 1989). The ambient temperature and molecular density are significant because it is necessary to produce the emission of radiation through interstellar atmosphere, which leads the experimental and theoretical studies of scientific area such as astrophysics, combustion physics and chemical physics.

Eriksson et al. (1925) reported the (0, 0) to (8, 10) bands of the $A^1\Pi - X^1\Sigma^+$ system of AlH molecule in the emission spectrum and also these bands observed in the region from 4158 to 5687 Å. For the first time, the $C^1\Sigma^+ - A^1\Pi$ transition had been identified near 4500 Å (Bengtsson et al., 1929). The radiative lifetimes for the $A^1\Pi$ state of AlH molecule had been measured by Baltayan et al. (1979). Besides, the theoretical values of radiative lifetimes for $A^1\Pi$ state had also been reported by several authors (Mauricio et al., 1987, Bauschlicher et al., 1988 and Yurchenko et al., 2018). Furthermore, the $\Delta\nu = -2$ sequence bands for $A^1\Pi - X^1\Sigma^+$ system of AlH molecule were observed in the emission spectra (Deutsch et al., 1987). Szajna et al. (2009 and 2011) had recorded six red degraded bands for $A^1\Pi - X^1\Sigma^+$ system in emission between 18,000 to 25,000 cm^{-1}, which consists of R, Q and P branches of the (0, 0), (0, 1), (1, 0), (1, 1), (1, 2) and (1, 3) bands.

The radiative transition parameters are astrophysically essential parameters, because they give the evidence for the possibility of presence of certain band system of diatomic molecules in solar environments. The diatomic molecular band intensities are predicted though the FC factors. As such, knowledge of FC factors and r-centroids are necessary for understanding the physico-chemical conditions of the formation

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Table 1
Molecular constants for the electronic states of AlH molecule.

Electronic states	Molecular constants ω_e (cm^{-1})	$\omega_e x_e$ (cm^{-1})	α_e (cm^{-1})	B_e (cm^{-1})	r_e (Å)	T_e (cm^{-1})
$X^1\Sigma^+$	1682.375	29.051	0.18706	6.39379	1.64735	–
$A^1\Pi$	1416.496	166.860	0.73254	6.38642	1.64830	23,638.329
$C^1\sum^+$	1575.336	125.5	0.55844	6.66802	1.61312	44,675.369

Note: ω_e - Vibrational frequency (cm^{-1}); $\omega_e x_e$ - Anharmonicity factor (cm^{-1}); α_e - Rotatioal constant in first term (cm^{-1}); B_e - Rotational constant in equilibrium (cm^{-1}); r_e - Internuclear distance(Å); T_e - Minimum electronic energy (cm^{-1})

Table 2
Radiative transition parameters for AlH molecule in $A^1\Pi - X^1\Sigma^+$ band system.

v',v''	$\lambda_{v',v''}$ (Å)	$I_{v'v''}$	$q_{v'v''}$	$\bar{r}_{v'v''}$ (Å)	$R_e(\bar{r}_{v'v''})$ (a.u)	$P_{v'v''}$	$S_{v'v''}$	$A_{v'v''}$ (x10^6 s^{-1})	$f_{v'v''}$ (x 10^{-2})	$\tau_{v'}$ (ns)
0,0	4260.59	9.69	0.969	1.685	0.574	0.319	1.001	16.727	4.554	
0,1	4577.36	0.32	0.032	2.343	0.837	0.022	0.070	0.948	0.298	
0,2	4930.85	0.09	0.009	2.009	0.704	0.004	0.014	0.151	0.055	
0,3	5326.96	0.02	0.002	2.178	0.771	0.001	0.004	0.032	0.014	56.00
1,0	4072.70	0.43	0.043	1.290	0.416	0.007	0.023	0.446	0.111	
1,1	4361.21	6.41	0.641	1.759	0.604	0.234	0.732	11.408	3.255	
1,2	4680.93	1.99	0.199	2.128	0.751	0.112	0.352	4.436	1.458	
1,3	5036.46	0.85	0.085	2.153	0.761	0.049	0.154	1.562	0.594	
1,4	5433.24	0.35	0.035	2.232	0.793	0.022	0.069	0.556	0.246	
1,5	5877.73	0.08	0.008	2.463	0.885	0.006	0.020	0.125	0.065	53.96
2,1	4223.24	2.20	0.220	1.633	0.553	0.067	0.211	3.622	0.969	
2,2	4522.36	0.70	0.070	1.742	0.597	0.025	0.078	1.092	0.335	
2,3	4853.37	1.72	0.172	2.126	0.750	0.097	0.304	3.433	1.213	
2,4	5220.76	1.89	0.189	2.226	0.790	0.118	0.370	3.362	1.375	
2,5	5629.86	1.65	0.165	2.297	0.819	0.111	0.347	2.512	1.194	71.32
3,1	4150.44	0.49	0.049	1.532	0.513	0.013	0.040	0.730	0.189	
3,2	4438.99	0.85	0.085	1.774	0.610	0.032	0.099	1.463	0.432	
3,3	4757.47	0.50	0.050	2.131	0.752	0.028	0.089	1.065	0.362	
3,4	5109.96	0.07	0.007	2.224	0.790	0.004	0.014	0.133	0.052	
3,5	5501.23	0.04	0.004	2.387	0.855	0.003	0.009	0.071	0.032	288.82

of the molecules in high temperature solar atmosphere. The electronic transition moment depends on the nature of electronic state wave function and the strong photon interaction with an eigen state. The band strength helps to study the opacity of the molecular species in solar atmosphere. The electronic transition moment and band strength are used to estimate the Einstein coefficients, radiative lifetime and oscillator strength. The radiative lifetime and oscillator strength give more information about the upper electronic state of diatomic molecules.

So far, only a partial set of FC factors for $A^1\Pi - X^1\Sigma^+$ system of AlH molecule had been reported by using RKR potential (Huron 1969) and MRCI (Multireference Configuration Interaction) potential (Nathan et al., 2011). Hence, in the present investigation, the complete set of radiative transition parameters are estimated for all the experimentally observed vibrational levels of $A^1\Pi - X^1\Sigma^+$ and $C^1\Sigma^+ - A^1\Pi$ systems of AlH molecule using molecular constants (Table 1) reported by Szajna et al. (2011). The estimated values of radiative transition parameters are listed in Table 2 and 4. A fresh search was carried out to identify the $A^1\Pi - X^1\Sigma^+$ (0, 0; 1, 1; 0, 1) band transitions of AlH molecule in the high resolution FTS umbral spectra obtained from the National Solar Observatory at Kitt Peak. For the confirmed transitions, equivalent widths are calculated for well resolved lines and thereby the effective rotational temperatures of the source are estimated.

2. Computational methods

The accuracy of the calculated FC factor and r-centroid values depends on the knowledge of the potential energy curves of the lower and upper electronic states, which are used in the radial Schrödinger equation to solve the rotation-less wave functions. In this manner, the RKR potential energy function yields reliable FC factor and r-centroid values for a band in an electronic transition with the help of the known molecular constants. The computation of the FC factor is made by Bates (1949) method of numerical integration according to the detailed procedure described by Sindhan et al. (2020). In this manner, the classical turning points of the vibrational levels are estimated with the help of RKR method. The electronic state wave functions have been estimated for the range of internuclear distance between 1.281 to 2.908 Å for $A^1\Pi - X^1\Sigma^+$ and 1.182 to 3.289 Å for $C^1\Sigma^+ - A^1\Pi$ systems of AlH molecule at the intervals of 0.01 Å. The radiative transition parameters are calculated for $A^1\Pi - X^1\Sigma^+$ and $C^1\Sigma^+ - A^1\Pi$ systems using molecular constants (Table 1). Accurate values of FC factor and r-centroid are computed with the knowledge of RKR potential and it leads, for a proper understanding of the intensity distribution in the molecular band system. The variation of electronic transition moment can be obtained from band intensities, FC factor and r-centroid. The FC factor and electronic transition moment help us to estimate the values of band strength, relative band strength, oscillator strength, Einstein coefficients and radiative lifetime.

The effective vibrational temperature can be obtained from a plot of $\log\left\{\sum_{v''}(I\lambda^4)_{v'v''}/\sum_{v''}S_{v'v''}\right\}$ against $G(v')$ (where $\lambda_{v'v''}$is the wavelength of the band, $S_{v'v''}$ is the relative band strength and $G(v')$ is the vibrational energy of the molecule in the level v'), a straight line can be obtained by the least square fit method and its slope will yield a value of the effective vibrational temperatures of the source.

The atlases of the sunspot umbral spectrum are available with a rich collection of identified as well as questionable molecular lines (Wallace et al., 1998 and 2000). The digital form of the sunspot spectrum downloaded through ftp from the NSO website (ftp://nsokp.nso.edu/pub/atlas). A total number of 122 (0, 0; 1, 1; and 0, 1 bands) rotational lines (Szajna et al., 2009) of $A^1\Pi - X^1\Sigma^+$ system of AlH molecule were carefully searched and the results were classified as present,

Table 3
Computed Wavenumber, FC factor, Einstein coefficient, oscillator strength and lifetime (ns) for various bands of the $A^1\Pi - X^1\Sigma^+$system in AlH molecule compared with experimental and theoretical data.

v',v''	$\overline{\nu}_{v'v''}$ (cm^{-1}) Present	Cal.[a]	$q_{v'v''}$ Present	Cal.[a]	Cal.[b]	$A_{v'v''}$ ($x10^6 s^{-1}$) present	Exp.[f]	Cal.[g]	$\tau_{v'}$ (ns) present	
0,0	23,470.93	23,470	0.969	0.961	0.966	16.727	15.200	9.028	56.00	[66±4][c]
0,1	21,846.65	21,847	0.032	0.035	0.024	0.948	0.027	0.004		[62][d]
0,2	20,280.48	20,280	0.009		0.009					[64.3][e]
0,3	18,772.43	18,772	0.002		0.001					[64.3][g]
1,0	24,553.74	24,554	0.043	0.027	0.033	0.446	1.530	0.810	53.96	[83±6][c]
1,1	22,929.42	22,929	0.641	0.633	0.745	11.408	10.200	5.407		[102][d]
1,2	21,363.28	21,363	0.199		0.135	4.436	0.296	0.166		[96.6][e]
1,3	19,855.22	19,855	0.085		0.065					[89.6][g]
2,1			0.220	0.167						
3,1			0.049	0.094						

[a] Huron (1969);.
[b] Nathan *et al.* (2011);.
[c] Baltayan et al. (1979).
[d] Mauricio et al. (1987);.
[e] Bauchlicher et al. (1988).
[f] Rice et al.(1992);.
[g] Yurchenko et al. (2018).

shoulder, bend, merged and doubtful according to the detailed procedure described by Sriramachandran et al. (2011).

The significant number of well resolved lines that have an intensity of at least one-tenth were selected for the estimation of equivalent width using a triangular profile approximation method. The effective rotational temperatures of the source were estimated from the following expression (Herzberg, 1950) as,

$$\log(W_{J''}/S_{J''}) = const. - \frac{Bhc}{2.3kT}J''(J''+1) \quad (1)$$

where, $W_{J''}$ is the equivalent width, $S_{J''}$ is the Hönl-London factor of the rotational line (J"), B is the rotational constant and T is the rotational temperature. In $J''(J''+1)$ versus $\log(W_{J''}/S_{J''})$ plot, a straight line can be obtained by the least square fit method and its slope will yield a value of the effective rotational temperatures of the source.

3. Results and discussion

3.1. Estimation of radiative transition parameters for alh molecule

In the $A^1\Pi - X^1\Sigma^+$ system, the radiative transition parameters were calculated with the help of RKR potential and the values are listed in Table 2. The FC factor clearly indicate that the (0, 0), (1, 1), (1, 2), (2, 1), (2, 3), (2, 4) and (2, 5) bands are most intense than the other observed bands. These intense bands are lying in the wavelength region from 4223 to 5630 Å. The FC factor values of most intense (0, 0) and (1, 1) bands are found to be 0.969 and 0.641 respectively. It is important to note that the FC factor values of (1, 1) band are about 66 percent of that of the (0, 0) band. Furthermore, these bands are observed at 4260.59 Å and 4361.21 Å, respectively. The $\Delta\nu = 0$ sequence band intensities are weaker except for the (0, 0) and (1, 1) bands. Moreover, the r-centroid value of (0, 0) band is slightly higher than the value of $(r'_e + r''_e)/2$, which shows that the potential energy curves for this transition is not fully anharmonic. The r-centroid sequence differences $(\Delta\overline{r}_{v'v''} = \overline{r}_{v'+1,v''+1} - \overline{r}_{v'v''})$ are less than 0.389 Å. Hence, it is clearly indicated that the potential energy curve is wide. The wavelength of this system increases with an increasing r-centroid values (except (0, 1) band). Therefore, this system is expected to be red degraded. This result is agreed very well with previous results reported by Nathan et al. (2011) (see Table 3). Furthermore, the electronic transition moments were estimated using the r-centroid method, obtained by the expression as,

$$R_e(\overline{r}_{v'v''}) = const.(4.030\overline{r}_{v'v''} - 1)\ 1.290\text{Å} \le \overline{r}_{v'v''} \le 2.463\text{Å} \quad (2)$$

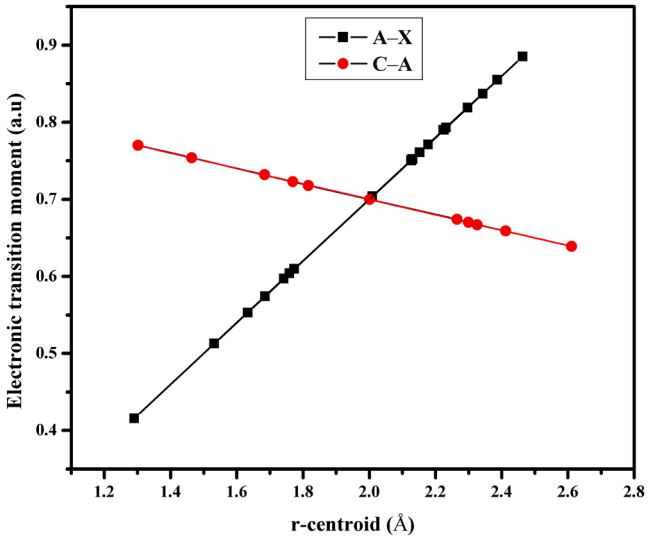

Fig. 1. Electronic transition moment versus r-centroid for the $A^1\Pi - X^1\Sigma^+$ and $C^1\Sigma^+ - A^1\Pi$ band systems of AlH molecule.

Hence, the electronic transition moment values are found relatively high in magnitude, and these values are slowly increasing with increasing r-centroid values (see Fig. 1). The band strength and Einstein coefficient values of (0, 0) band are found to be 0.319 and 16.727×10^6 S^{-1} respectively, which are much higher than the other observed bands. Hence, it is indicated that this band is stronger. The oscillator strength values of (0, 0) and (1, 1) bands are found to be 0.0455 and 0.0325 respectively. Moreover, the radiative lifetimes of $A^1\Pi$ state are estimated in the range from $\tau(v' = 0) = 56.00$ ns to $\tau(v' = 3) = 288.82$ ns.

Secondly, for the $C^1\Sigma^+ - A^1\Pi$ system, the radiative transition parameters were also calculated and they are tabulated in Table 4. The FC factors clearly indicate that the (0, 0), (1, 1), (1, 2), (2, 1), (2, 2), (2, 3), (3, 2), (3, 3) and (4, 3) bands are most intense than the other observed bands. All the intense bands are lying in the wavelength region from 4410 to 4850 Å. The most intensity of (0, 0) band is located at 4733.32 Å and its FC factor is 0.972. Further, the FC factor of (1, 1) band is 0.822, which is 85 percent of that of (0, 0) band. The $\Delta v = 0$ sequence bands have weaker intensity, except for (0, 0), (1, 1) and (2, 2) bands. Furthermore, the intensities of the $\Delta v = \pm 1$ sequence bands are also found weak except for (4, 3) band. Subsequently, the r-centroid value of

Table 4
Radiative transition parameters for AlH molecule in $C^1\Sigma^+ - A^1\Pi$ band system.

v', v''	$\lambda_{v',v''}$ (Å)	$I_{v'v''}$	$q_{v'v''}$	$\bar{r}_{v'v''}$ (Å)	$R_e(\bar{r}_{v'v''})$ (a.u)	$P_{v'v''}$	$S_{v'v''}$	$A_{v'v''}$ (x10^6 s^{-1})	$f_{v'v''}$ (x 10^{-2})	$\tau_{v'}$ (ns)
0,0	4733.32	9.72	0.972	1.684	0.732	0.520	1.000	9.879	6.680	50.31
1,0	4454.12	0.47	0.047	2.265	0.674	0.021	0.041	0.978	0.291	
1,1	4679.82	8.22	0.822	1.816	0.718	0.424	0.815	16.772	5.510	
1,2	4849.82	1.03	0.103	1.464	0.754	0.058	0.112	2.078	0.733	
1,3	4949.52	0.18	0.018	1.302	0.770	0.011	0.021	0.356	0.131	49.45
2,1	4455.99	1.59	0.159	2.299	0.670	0.071	0.137	3.270	0.974	
2,2	4609.86	5.18	0.518	2.001	0.700	0.254	0.488	10.496	3.346	
2,3	4699.84	1.22	0.122	1.769	0.723	0.064	0.123	2.490	0.825	61.52
3,2	4441.49	3.82	0.382	2.412	0.659	0.166	0.319	7.668	2.269	
3,3	4524.96	1.00	0.100	2.326	0.667	0.045	0.086	1.948	0.598	104.00
4,3	4410.93	4.54	0.454	2.611	0.639	0.185	0.356	8.750	2.554	114.29

Note: In Table 2,3&4; v', v'' - transition band; $\lambda_{v'v''}$-wavelength (Å); $I_{v'v''}$- band intensity; $q_{v'v''}$- FC factor; $\bar{r}_{v'v''}$- r-centroids; $R_e(\bar{r}_{v'v''})$- electronic transition moment (a.u); $P_{v'v''}$- band strength; $S_{v'v''}$- relative band strength; $A_{v'v''}$ - spontaneous emission rate (s^{-1}); $f_{v'v''}$- absorption band oscillator strength; $\tau_{v'}$ - radiative lifetime (ns).

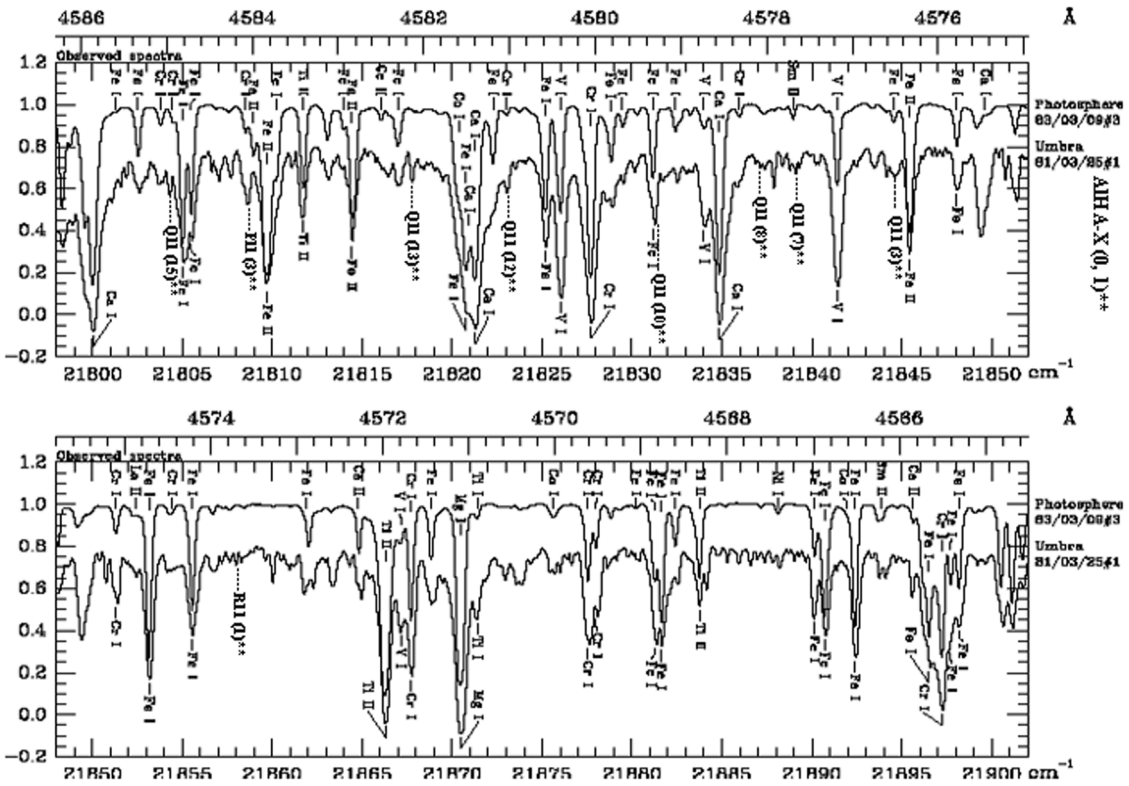

Fig. 2. Section of the sunspot umbral spectrum with identified for the $A^1\Pi - X^1\Sigma^+$ (0, 1) band system of AlH molecular lines.

(0, 0) band is slightly larger than the value of $(r'_e + r''_e)/2$, which shows that the potential energy curves for this transition is not fully anharmonic. The sequence difference is found less than 0.325 Å, which suggests that the potentials are wide. In addition, the r-centroids increase with decrease in wavelength of this system, hence this system is expected to be violet degraded. The electronic transition moments of this system is

$$R_e(\bar{r}_{v'v''}) = const.(1 - 0.111\bar{r}_{v'v''})1.302\text{Å} \leq \bar{r}_{v'v''} \leq 2.611\text{Å} \quad (3)$$

Accordingly, the electronic transition moment is relatively large in magnitude, and these values decrease slowly with increasing r-centroid values (see Fig. 1). The band strength and Einstein coefficient values of (0, 0) band are found to be 0.520 and 9.879 $\times$ 10^6 S^{-1} respectively, which are much higher than the other observed bands. Hence, it is indicated that this band is stronger. Moreover, the oscillator strength of (0, 0) band is found as 0.0668. The radiative lifetime of the $C^1\Sigma^+$ state is found as τ (v'=0) = 50.31 ns. Furthermore, the radiative lifetime of the $C^1\Sigma^+$ state is increasing slowly from v'=0 to v'=4 except v'=1 level.

3.2. Identification of ALH molecular lines

A total number of 122 rotational lines of the $A^1\Pi - X^1\Sigma^+$ system of (0, 0), (1, 1) and (0, 1) bands was carefully searched on the sunspot umbral spectra and the identification were classified as present, shoulder, bend, merged and doubtful. However, 27 lines of the (0, 0) band, 16 lines of the (1, 1) band and 26 lines of the (0, 1) bands were identified as present, shoulder and atomic line in sunspot hot umbral spectra (sample spectra in Fig. 2). Although, 3 lines of the (0, 0) band, 1 line of the (1, 1) band and 2 lines of the (0, 1) band were identified as bend. Further, only seven AlH lines 23,139.07 cm^{-1} (Fe I) for (0, 0), 22,926.94 cm^{-1} (Ti I), 22,955.25 cm^{-1} (Ca I) for (1, 1) and 21,651.78 cm^{-1} (Ti I), 21,728.62 cm^{-1} (Fe I), 21,821.19 cm^{-1} (Ca I) and 21,881.35 cm^{-1} (Fe I) for (0, 1) bands are perfectly match with strong atomic lines. The observed I-

Table 5
Estimated equivalent width values for the $A^1\Pi - X^1\Sigma^+$ transition lines of the AlH molecule.

Transition	Branch	J	W.No (cm^{-1})	Equivalent width (mÅ)
0,0	R11	3	23,515.58	83.531
		8	23,556.14	18.415
		9	23,561.69	14.165
		10	23,566.21	57.368
		11	23,569.59	27.622
		16	23,564.71	114.458
	Q11	1	23,470.34	30.930
		3	23,467.45	154.171
		5	23,462.12	84.937
		7	23,454.12	24.744
		8	23,449.00	18.654
		9	23,443.07	60.268
		10	23,436.26	31.569
		11	23,428.48	17.937
		13	23,409.67	80.357
		16	23,371.40	86.548
		17	23,355.31	173.095
	P11	8	23,354.51	67.315
		9	23,337.23	25.003
		11	23,300.44	15.146
		16	23,191.77	91.348
		17	23,166.24	23.448
1,1	R11	0	22,939.19	42.735
		3	22,960.62	25.472
		4	22,964.09	34.933
		5	22,965.57	50.459
		6	22,964.86	27.655
	Q11	2	22,923.59	24.838
		3	22,918.51	42.370
		5	22,902.93	18.506
		6	22,892.19	19.569
		7	22,879.35	36.963
	P11	2	22,902.50	14.732
		3	22,886.96	70.939
		8	22,782.57	36.950
0,1	R11	1	21,857.88	3.840
		5	21,914.54	1.637
		7	21,934.84	6.548
		8	21,944.25	24.010
		13	21,980.57	14.655
		15	21,987.74	12.212
		16	21,989.06	16.283
	Q11	3	21,844.58	15.444
		7	21,839.30	5.516
		8	21,837.10	5.516
		10	21,831.29	39.713
		12	21,823.04	23.166
		13	21,817.77	8.825
		15	21,804.29	15.858
		16	21,795.77	9.982
		17	21,785.77	10.537
	P11	3	21,808.60	29.785
		4	21,795.82	9.982
		6	21,769.70	6.655
		15	21,634.43	8.433

Note: J – Quantum number; W.No – Wavenumber (cm^{-1}); W – Equivalent width (mÅ).

parameter and the estimated C-index values are $I = 29$; C = 18, $I = 15$; C = 8 and $I = 24$; C = 21 for (0, 0), (1, 1) and (0, 1) bands respectively. The I-parameter is found to be conveniently higher than the C-index of all the band system. Therefore it is evident that the possible presence of AlH molecule in the sunspot umbra. A significant number of (55 lines) well resolved lines met the requirements for ((0, 0), (1, 1) and (0, 1)) $A^1\Pi - X^1\Sigma^+$ bands. A list of well resolved lines and their measured equivalent widths are tabulated in Table 5.

3.3. Estimation of effective temperatures for ALH molecule

The effective vibrational temperature for the $A^1\Pi - X^1\Sigma^+$ and $C^1\Sigma^+ - A^1\Pi$ systems of AlH molecule was calculated from the plot of $\log\left\{\sum_{v''}(I\lambda^4)_{v'v''}/\sum_{v''}S_{v'v''}\right\}$ against $G(v')$ as shown in Fig. 3 and a straight line is obtained by using least square fit method. From these slopes, the effective vibrational temperatures are obtained as 5682 K for $A^1\Pi - X^1\Sigma^+$ and 3472 K for $C^1\Sigma^+ - A^1\Pi$ systems assuming variation of electronic transition moment.

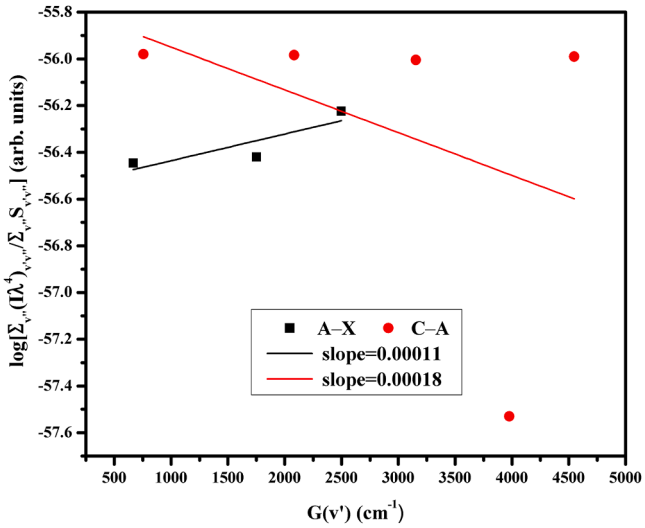

Fig. 3. Graph showing the straight line is obtained by plotting of $\log\left[\sum_{v''}(I\lambda^4)_{v'v''}/\sum_{v''}S_{v'v''}\right]$ versus $G(v')$ for the $A^1\Pi - X^1\Sigma^+$ and $C^1\Sigma^+ - A^1\Pi$ band systems of AlH molecule.

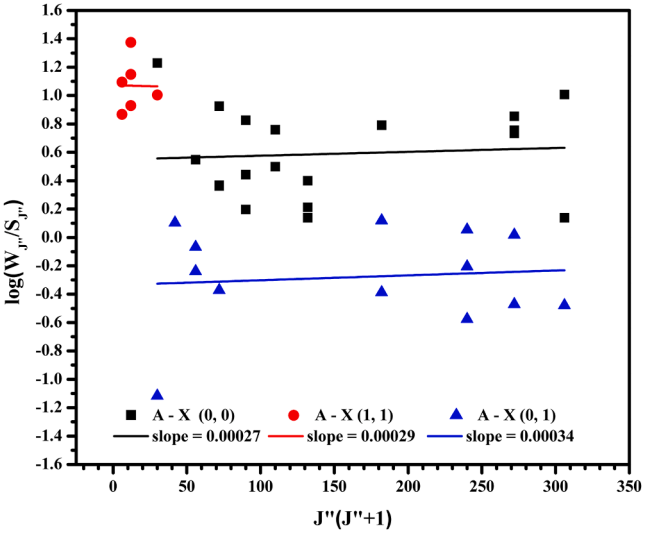

Fig. 4. Graph showing the straight lines are obtained by plotting of $\log(W_{J''}/S_{J''})$ against $J''(J''+1)$ for the $A^1\Pi - X^1\Sigma^+$ (0, 0), (1, 1) and (0, 1) bands system from hot Umbral sunspot (UsS) data.

The effective rotational temperatures of the $A^1\Pi - X^1\Sigma^+$ (0, 0; 1, 1 and 0, 1) bands system were determined from the plot shown in Fig. 4. Therefore, the effective rotational temperatures obtained from the slopes of $A^1\Pi - X^1\Sigma^+$ (0, 0; 1, 1 and 0, 1) band systems are found to be 2315 K, 2155 K and 1838 K for hot umbra respectively. There is a 20 percent of possible error in this estimation, due to underestimation of some observed lines. Earlier, the reported vibrational and average rotational temperatures of AlO molecule were 3600 (400) K and 1880 (100) K, respectively (Mentall et al. 1967 and Sriramachandran et al.,

2013). Sindhan et al. (2020) reported that the effective vibrational and rotational temperatures of the $B^4\Sigma^- - X^4\Sigma^-$ system of AlC molecule as 2706 K and 3722 K respectively. The rotational temperature of MgH molecule was estimated in the range of 3000 to 4000 K (Wohl 1970; Webber 1971; Sotirovski 1971 and Wallace et al., 1999). Sriramachandran et al. (2016) reported the high value of effective vibrational temperature for $d^3\Pi_g - a^3\Pi_u$ system of C_2 molecule as 5530 ± 1400 K. Mulchaey (1989) reported the average rotational temperature of FeH molecule as 1740 K. Sriramachandran et al. (2011) reported the effective vibrational temperature of CrH molecule as 1888 ± 256 K for $A^6\Sigma^+ - X^6\Sigma^+$ system. Therefore, the estimated radiative transition parameters and effective temperatures serve as the evidence of the presence of AlH molecular lines in the solar spectrum. Hence, the presence of AlH molecular lines in the solar spectrum provides the likelihood to study different layers of solar atmosphere and is very much useful for detecting umbral oscillations of abundances of molecules.

Author statement

Sindhan, R: Conceptualization, Writing – original draft, Fortran pogram, Investigation, Validation, Visualization. **Sriramachandran, P:** Conceptualization, Writing – original draft, Fortran pogram, Validation. **Shanmugavel, R:** Conceptualization, Resources, Fortran pogram. **Ramaswamy, S:** Writing – review & editing, Conceptualization, Investigation, Validation, Visualization, Supervision.

CRediT authorship contribution statement

R. Sindhan: Conceptualization, Writing – original draft, Investigation, Validation, Visualization. **P. Sriramachandran:** Conceptualization, Writing – original draft, Validation. **R. Shanmugavel:** Conceptualization, Resources. **S. Ramaswamy:** Writing – review & editing, Conceptualization, Investigation, Validation, Visualization, Supervision.

Declaration of Competing Interest

I am enclosing here with an original research article entitled "**On the Effective Temperature of Large Sunspot Umbra Using AlH Molecular Lines**" for publication in your esteemed journal for possible evaluation. With the submission of this manuscript I would like to undertake that the above mentioned manuscript has not been published elsewhere, accepted for publication elsewhere or under editorial review for publication elsewhere; and that all co authors listed below have agreed to have seen and approved the manuscript for submission.

Data availability

Data will be made available on request.

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