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Solar spectroscopy at ARIES

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Abstract. Identification of Fraunhofer lines with the known atomic and molecular absorbers and predictions leading to such efforts have been a challenging area of study crowned with occasional success. Such studies have also lead to (i) a determination of abundances of elements and their isotopes, (ii) valuable information on model atmospheres and (iii) use of Sun as a laboratory source to determine such atomic and molecular parameters as the oscillator strengths. We summarize and review here the work done in the last four and a half decades in the area of solar spectroscopy at the Aryabhatta Research Institute of observational sciencES (ARIES in short) with a view to pick up new and interesting areas for future investigations in the light of tremendous progress made elsewhere in observations of the sun and in the laboratory studies.

Keywords : Sun, Spectroscopy, Model atmosphere, Molecules, Oscillator Strengths

1. Introduction

The work at ARIES has been focused on theoretical investigations on molecules in sunspots, photosphere and faculae with a few papers on atomic lines and where possible to compare the results with published observational data. An attempt without much success was made to develop a 25 cm horizontal f/66, 6° off-axis skew cassegrain telescope forming a 16 cm solar image together with a high dispersion double pass spectrograph. Work on the then contemporary scene have been summarized in reviews by Pande (1972) and Sinha (1991, 1993, 1998).

Melendez and Barbuy (1999) extended our work in the J and H bands of the solar spectrum to include several hundred additional lines for a determination of log gf

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values. Also, based on our predictions, Berdyugina and Livingston (2002) reported detection of the mercapto radical SH in the solar photosphere. Though large equivalent widths (EWs in short) are predicted in the cool sunspot umbrae, in view of strong scattered light in UV from the surrounding photosphere, the observational results for SH in sunspots were stated unsatisfactory by these authors. Amongst the more recent work in solar molecular spectroscopy, the work by Sonnabend et al. (2006) and Kleint et al. (2011) can be cited. We feel prompted to summarize our work with a view to identify and pick up new areas for studies.

In the following, it is not our intention to underplay or to take away any credit from colleagues who independently worked elsewhere on similar lines. In fact, we received lot of help, support and encouragement from colleagues working in frontier areas of research.

2. Predictions on line identifications

The molecules AlO, BO, CaO, CH_2, CO_2, CS, HCl, HCN, HCO, H_2, H_2S, NaH, NH_2, NH_3, NO, NS, N_2, O_2, PH, PO, SH, SiO, SO, S_2, TiO_2, VO, YO, and AlH^+, CO^+, H_2^+, MgH^+, NH^+, OH^+, SH^+, SiH^+ were considered important in sunspots on the basis of number/partial pressure considerations. EW calculations showed that the vibration–rotation lines of HCl, HF, MgH, NO, SiH and SiO and UV transitions in MgH^+, NO, O_2, PH, PO, SH, and SiO were expected present and also that the isotopic lines of SiO and SH could additionally be looked for in the umbral spectrum. The molecules BO, HI, HBr, and HCN were found not detectible. SiO lines were detected in the spectrum by Glenar et al (1983). Dissociation equilibrium calculations showed that the molecules CS, HCl, HF, SH, SiO and SO form in sufficient numbers and that they could show up in the corresponding photospheric spectrum. Further, the concentrations of the considered species dropped in the order H_2^+, CO^+, OH^+, NO^+, O_2^+, and N_2^+. EW calculations indicated that observable but very weak lines of CS, C_2 (Phillips, Ballik–Ramsay and Mulliken bands), MgH^+ and SH were also there in the photospheric spectrum. Some of these predictions were later commented upon or supported with observations by Lambert and Mallia (1974), Grevesse et al (1977) and Brault et al (1982). We identified additional lines of the C_2 Swan system in the photospheric spectrum. CO^+, HeH^+ and NO-gamma system were found absent and we could not convince ourselves with the detection of CH^+ in photosphere.

We found that in the facular spectra, CH^+ could show up whereas MgH^+, OH^+ and SiH^+ could also be present but AlH^+, CN^+, CO^+, N_2^+ and NH^+ were not detectible.

3. Sensitivity to model atmospheres

Using TiO lines of the alpha system, the rotational temperature, T_{rot}, consistent with Zwaan's sunspot model was obtained. Also, center to limb (CL in short) behavior of

T_{rot} for the infrared bands of the SiO in different sunspot models was theoretically investigated and the results were found to differ from each other by about 150 to 400 K.

For the MgH green band lines in sunspots, an inequality $W_{cal} > W_{obs}$ was found and to resolve the discrepancy, the role of the penumbral blurring and scattered light from umbral dots was stressed upon. We also suggested a revision of the Δ v $\neq$ 0 oscillator strengths.

The concentrations of molecules was shown to vary with magnetic field strengths and the EW of a representative CO line was found to linearly increase and subsequently attain a saturation value with increase in magnetic field strength. The simultaneous observations in photosphere and spots for C_2, MgH and TiO, found in a narrow spectral range, was theoretically demonstrated a good probe to sense the evolution of sunspots with increasing magnetic fields/umbral diameters and also to sense if the sunspots are different at different phases of the solar cycle.

Our observations on photospheric CH lines at different CL distances for T_{rot} do not help decipher a change in the values in view of a large scatter. The use of Delbouille et al.'s (1973) atlas as well as fresh observations for the CN and CH lines for a determination of doppler widths has shown that the same varies linearly with EW. Also. a variation in the turbulence velocities towards the limb was inferred.

Observations at the center of the solar disc for the photospheric C_2 and MgH were found not to reproduce the model based rotational temperatures. The problem was further investigated in detail and we utilized the published EWs at different CL distances from Withbroe (1968) but instead, a spurious rise in T_{rot} at a near limb position was found. The discrepancy was resolved by accounting for saturation in lines which is very important for C_2. However, we still faced a small problem for $\mu = 0.2$ on the solar disc; against a model based $T_{rot} = 5110 \pm 10$, an observed value $T_{rot} = 5400 \pm 240$ was obtained. It lead us to point out that the temperatures in the outer layers of the photospheric model due to Holweger and Müller (1974) needed slight increases. The task was later accomplished independently by Grevesse and Sauval (1999) in order to solve the controversy surrounding iron abundances. However, the same does not remove the mismatch in T_{rot} values.

The behavior of a few lines of the Balmer, Paschen and Brackett series of hydrogen and their CL variation in representative facular and photospheric models were investigated with the conclusion that these lines were sensitive probes for the chosen model atmospheres. Similar conclusions on the use of vibration–rotation lines of CO and the red and the violet system lines of CN were reached. EWs for the CH, C_2, MgH, NH, OH and SH lines were calculated for future comparison with observations and it was found that CH, NH and OH could be good candidates for testing model atmospheres. Rotational temperatures, T_{rot}, for the vibration–rotation lines of CO were reported consistent with the chosen model atmospheres.

4. Sun as a laboratory source

Utilizing the published literature on solar spectrum, the oscillator strengths of the Phillips bands of C_2, the green bands of MgH and that of SiH^+ were derived. The dissociation energy, D_0^0, for the CN molecules was found to lie in the range 7.66 to 7.76. Log gf values of Fe, Fe^+, Ni, Sc, Si, Ti and V in the spectral range 6209–6273 Å were derived and so also for about 300 lines due to 17 different atomic species in the J and H bands.

Franck–Condon factors for UV transitions in AlF, CaH, P_2, SiCl, SiF and also the partition functions and the dissociation constants for HeH^+ and MgH were calculated. For the H_3^+ ion only the partition functions were calculated. We made suggestions on life time and wave number measurements of the infrared transitions in MgO. The wave numbers have since become available (Kagi et al, 1994). Rotational and vibrational constants for CaH^+ were theoretically calculated and reported. Habli et al (2011) and Abe et al (2012) have published latest results on this ionic molecule.

5. Conclusions

Thus, it is seen that fresh attempts towards identification of spectral lines, towards refining a model atmosphere and towards a study of evolution of sunspots with the help of molecular lines hold promise for future studies. A beginning in this direction can be made with the available FTS solar atlases. In the infrared, vibration–rotation transitions in MgH, NO and SiH and in the ultraviolet the electronic transitions in MgH^+, NO, O_2, PH, PO, SH and SiO could be important for identifications in the solar spectrum. Oscillator strength estimates, theoretical and/or experimental, for SH are needed to effect a check on the only available results (theoretical) due to Henneker and Popkie (1971). A complete bibliography of our work is available at www.aries.res.in/research/solar/Bibliography.pdf.

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