Planetary and Space Science xxx (2017) 1–8

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Constraints on interstellar dust models from extinction and spectro-polarimetry

R. Siebenmorgen [a,*], N.V. Voshchinnikov [b], S. Bagnulo [c], N.L.J. Cox [d]

[a] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748, Garching b. München, Germany
[b] Sobolev Astronomical Institute, St. Petersburg University, Universitetskii prosp. 28, St. Petersburg, 198504, Russia
[c] Armagh Observator and Planetariumy, College Hill, Armagh, BT61 9DG, UK
[d] Anton Pannekoek Institute for Astronomy, University of Amsterdam, NL-1090 GE, Amsterdam, The Netherlands

ARTICLE INFO

Keywords:
Dust
Extinction
Polarisation
Interstellar medium

ABSTRACT

We present polarisation spectra of seven stars in the lines-of-sight towards the Sco OB1 association. Our spectra were obtained within the framework of the Large Interstellar Polarization Survey carried out with the FORS instrument of the ESO VLT. We have modelled the wavelength-dependence of extinction and linear polarisation with a dust model for the diffuse interstellar medium which consists of a mixture of particles with size ranging from the molecular domain of 0.5 nm up to 350 nm. We have included stochastically heated small dust grains with radii between 0.5 and 6 nm made of graphite and silicate, as well as polycyclic aromatic hydrocarbon molecules (PAHs), and we have assumed that larger particles are prolate spheroids made of amorphous carbon and silicate. Overall, a dust model with eight free parameters best reproduces the observations, and is in agreement with cosmic abundance constraints. Reducing the number of free parameters leads to results that are inconsistent with the cosmic abundances of silicate and carbon. We found that aligned silicates are the dominant contributor to the observed polarisation, and that the polarisation spectra are best-fit by a lower limit of the equivolume sphere radius of aligned grains of 70–200 nm.

1. Introduction

Our understanding of many astrophysical processes, ranging from galaxy evolution to stellar and planetary formation, depends on our knowledge of the cosmic dust (e.g. Draine, 2009, Asano et al., 2014). Dust and molecular gas co-exist in interstellar clouds, and the properties of both components are mutually dependent through various chemical reactions and physical (photon) processes.

Interstellar dust grains absorb, scatter, and polarise the background radiation. The observed wavelength dependencies of extinction, emission and polarisation of the radiation coming from background sources may allow us to characterise the dust of the diffuse interstellar medium (ISM) (Désert et al., 1990, Siebenmorgen and Krügel, 1992, Kim et al., 1994, Dwek et al., 1997, Weingartner and Draine, 2001, Draine and Li, 2007, Draine and Fraisse, 2009, Jones et al., 2013, Köhler et al., 2014, Voshchinnikov, 2012, Siebenmorgen et al., 2014, Voshchinnikov et al., 2016).

The absolute extinction is often represented as a function $A(\lambda^{-1})$ normalised by the extinction value in the visible band A_V. This extinction curve $A(\lambda^{-1})$ has been observed for hundreds of sight lines (Fitzpatrick and Massa, 1986, 1990, Calzetti et al., 1994, Papaj and Krelowski, 1992, Fitzpatrick and Massa, 2007, Valencic et al., 2004, Gordon et al., 2009). It varies with wavelength and approaches zero at longer wavelengths. In the optical, the extinction curves tend to follow a relation that depends on the total-to-selective extinction $R_V = A_V/E_{B-V}$ (Cardelli and Savage, 1988), where $E_{B-V} = (B- V)- (B-V)_0$ is the colour excess given by the observed magnitude difference at B and V of the star and of identical unreddened star (Johnson et al., 1968, Bless and Savage, 1970, Massa et al., 1983, Mathis, 1990). Flat extinction curves with large R_V values are measured towards denser regions. The parameter R_V is also a rough indicator of grain size: sight lines of low R_V values are thought to be characterised by smaller grains than sight lines with higher R_V values.

Extinction curves may be modified by scattering of photons from dust clouds in or out of the line of sight. Scicluna and Siebenmorgen (2015) have shown that the observed extinction is not significantly modified by scattering from dust clouds at distance smaller than 1 kpc. For such nearby stars, the extinction curves provide crucial information on the composition and size distribution of the interstellar dust.

* Corresponding author.
E-mail address: Ralf.Siebenmorgen@eso.org (R. Siebenmorgen).

http://dx.doi.org/10.1016/j.pss.2017.05.007
Received 19 September 2016; Received in revised form 10 May 2017; Accepted 12 May 2017
Available online xxxx

Please cite this article in press as: Siebenmorgen, R., et al., Constraints on interstellar dust models from extinction and spectro-polarimetry, Planetary and Space Science (2017), http://dx.doi.org/10.1016/j.pss.2017.05.007

Also polarisation spectra constrain sizes, shape and composition of the dust grains. Asymmetrical dust grains are most likely aligned with the magnetic field and polarise the light (Andersson et al., 2015). So far, the majority of polarisation measurements are obtained in optical (*UBVR*) and near infrared (*IJHK*) broadband filters (Whittet, 2003). The observed polarisation spectra generally have a quasi-parabolic shape (Serkowski et al., 1975). The position of the polarisation maximum and the width of the polarisation spectrum varies from star to star, and this diversity is probably due to different local conditions affecting the alignment efficiencies and the grain sizes (Voshchinnikov and Hirashita, 2014). Insight into the shape and size distribution and composition of interstellar grains may come from detailed physical models (Draine and Fraisse, 2009, Voshchinnikov, 2012, Siebenmorgen et al., 2014, Voshchinnikov et al., 2016).

We have started a Large Interstellar Polarisation Survey (LIPS; PI: N.J.L. Cox) with the aim of determining the chemical composition and size distribution of interstellar dust in numerous sight-lines. In this paper we present spectro-polarimetry of seven early-type stars obtained with the FORS2 instrument (Appenzeller et al., 1998) of the ESO VLT. Spectra cover the wavelength range 365–920 nm and have a resolution of about 880. For our sample of stars, extinction curve measurements are available by Valencic et al. (2004). The seven stars are located towards sight lines of the Scorpius–Centaurus Association (called Sco OB1).

This paper is organised as follows. In Sect. 2 we present our new data. In Sect. 3 we present a dust model and a procedure for fitting the extinction and polarisation curve of an object simultaneously. Sect. 4 presents the result of our modeling efforts. In Sect. 5 we give a summary of our main results.

2. Observations

From the original LIPS target list we selected a small sub-sample comprising seven close-by lines-of-sight towards the Sco OB1 region, including two possible association members, HD 151804, HD 152235 that are supergiants stars.

In Fig. 1 we show the target location in galactic coordinates overlaid to an extinction map produced from DSS (Dobashi et al., 2005). The distance for HD 153919 is 1.7 kpc (Ankay et al., 2001) while the other stars (HD 151804, HD 152235, HD 152248, HD 152408), are confirmed Hipparcos members of Sco OB1 which is at an estimated distance of 2 kpc. The stars HD 152235, HD 152248, HD 152249 and HD 152408, are close to each other in the sky, and have low polarisation efficiency of $p_{\max}/E(B-\ V)\sim 1-\ 2$. More detailed target information is given in Table 1.

2.1. Extinction

Extinction curves are usually measured with ground-based facilities in the near IR, optical and UV photometric bands, and, at shorter UV wavelengths, by the IUE $(3.3\,\mu\mathrm{m}^{-1}<\lambda^{-1}<8.6\,\mu\mathrm{m}^{-1})$ and FUSE $(3.3\,\mu\mathrm{m}^{-1}<\lambda^{-1}<11\,\mu\mathrm{m}^{-1})$ satellites, which provide spectroscopy at a resolution of ~ 0.5 nm. Extinction data are often fit by a third order polynomial and a Drude profile to account for the 217 nm extinction bump (Fitzpatrick and Massa, 1990, 2007). Extinction curves of our sample stars are provided by Valencic et al. (2004) using IUE data, while FUSE observations at $\lambda^{-1}<8.6\,\mu\mathrm{m}^{-1}$ are not available for our stars. Following Gordon et al. (2009), we decreased the value of the parameter describing the far UV rise as given by Valencic et al. (2004) by $\sim 8\%$; other fit parameters determined with IUE data, or those obtained using the combined IUE and FUSE data sets, are broadly consistent (Gordon et al., 2009). In order to fit the extinction data in the *UBVJHK* bands we have used the R_V parametrisation by Fitzpatrick (2004).

Table 1
Observing sample.

Target (1)	Sp.Type (2)	l (3)	b (4)	V (5)	E (B-V) (6)	R(V) (7)
HD 149404	O8.5Iab(f)p	340.5375	+03.0058	5.87	0.62 ± 0.06	3.53 ± 0.38
HD 151804	O8Iaf	343.6156	+01.9378	5.29	0.30 ± 0.03	4.33 ± 0.30
HD 152235	B0.5Ia	343.3111	+01.1041	6.38	0.71 ± 0.06	3.13 ± 0.25
HD 152248	O7Iabf + O7Ib	343.4644	+01.1839	6.15	0.41 ± 0.04	3.68 ± 0.26
HD 152249	OC9Iab	343.4488	+01.1649	6.65	0.46 ± 0.10	3.54 ± 0.45
HD 152408	O8Iape	344.0836	+01.4909	5.92	0.42 ± 0.05	4.17 ± 0.33
HD 153919	O6Iafcp	347.7544	+02.1735	6.78	0.51 ± 0.04	3.87 ± 0.22

NOTES – Target name (1), Spectral type of star (2), galactic longitude l (3) and latitude b (4), V from Simbad (5), $E(B-\ V)$ (6) and $R(V)$ (7) by Valencic et al. (2004).

Extinction curves of the ISM that are derived from observations of supergiants might be affected by systematic errors that are larger than for main sequence stars. For supergiants it is difficult to disentangle the ISM extinction from contribution by circumstellar dust, and it is difficult in finding an unreddened supergiant with spectral class. The extinction curves of our sample stars have typical uncertainties of 10% in the optical/UV with somewhat larger uncertainties in the near infrared.

2.2. Polarimetry with FORS2

Linear spectro-polarimetric observations were obtained with the FORS2 instrument of the ESO VLT (Appenzeller et al., 1998) within the context of the Large Interstellar Polarisation Survey (LIPS, PI: N.J.L. Cox). All observations were obtained with grism 300 V, which covers the spectral range 365– 920 nm, using the so-called beam-swapping technique recommended in the FORS user manual, and described in detail, e.g., by Bagnulo et al. (2009). With a 0.5″ slit width, our observations have a nominal spectral resolution $\lambda/\Delta\lambda\sim 880$. Data were reduced following the guidelines by Bagnulo et al. (2009). Note that null profiles could not be determined since observations were obtained with four exposures only (at the following four positions of the retarder wave-plate: 0°, 22.5°, 45°, 67.5°). To improve the S/N ratio, we decided to rebin our spectra, by degrading the spectral resolution to $\lambda/\Delta\lambda\sim 50$. In the rebinning process, outliers (e.g., due to cosmic-rays) were rejected with a 3 σ clipping algorithm; after outlier rejection, we calculated the weighted mean of the pixel values, and estimating 1 σ error from the variance of the polarisation of the original bin. In Table 2 we specify the observing date

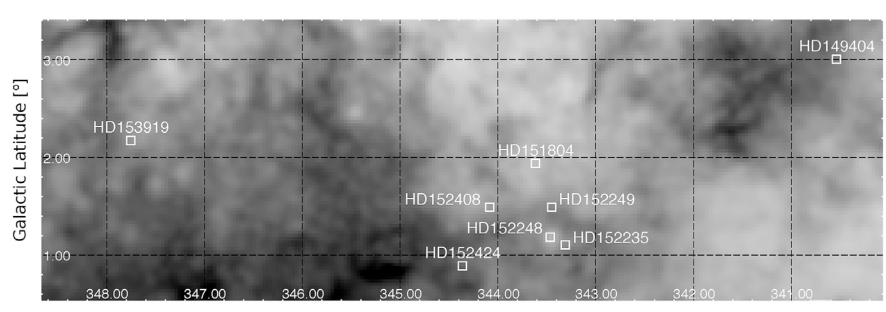

Fig. 1. Observed stars towards Sco OB1 displayed on top of an extinction map produced from DSS (Dobashi et al., 2005).

Please cite this article in press as: Siebenmorgen, R., et al., Constraints on interstellar dust models from extinction and spectro-polarimetry, Planetary and Space Science (2017), http://dx.doi.org/10.1016/j.pss.2017.05.007