A Survey of AU-Scale Na I Structure in the Diffuse Interstellar Medium

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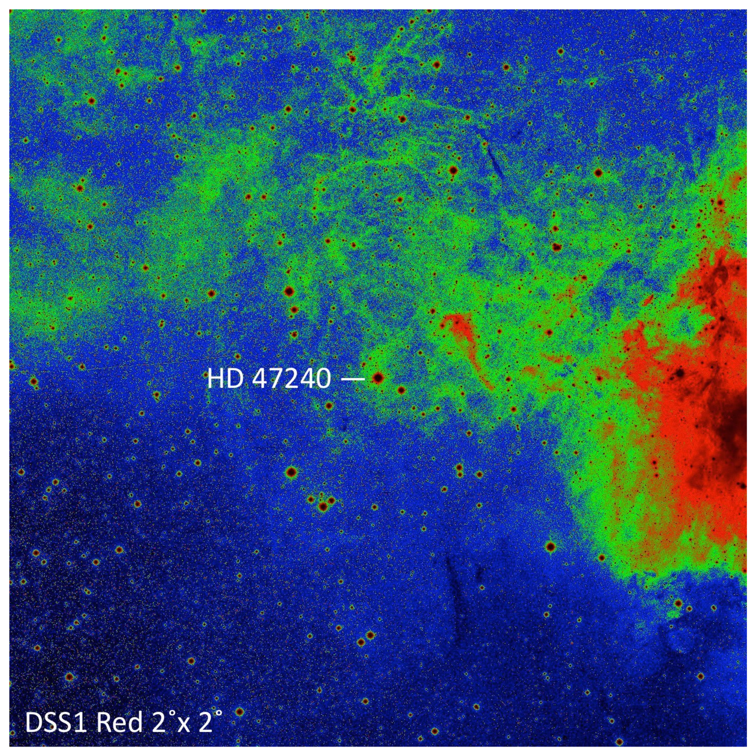
Introduction

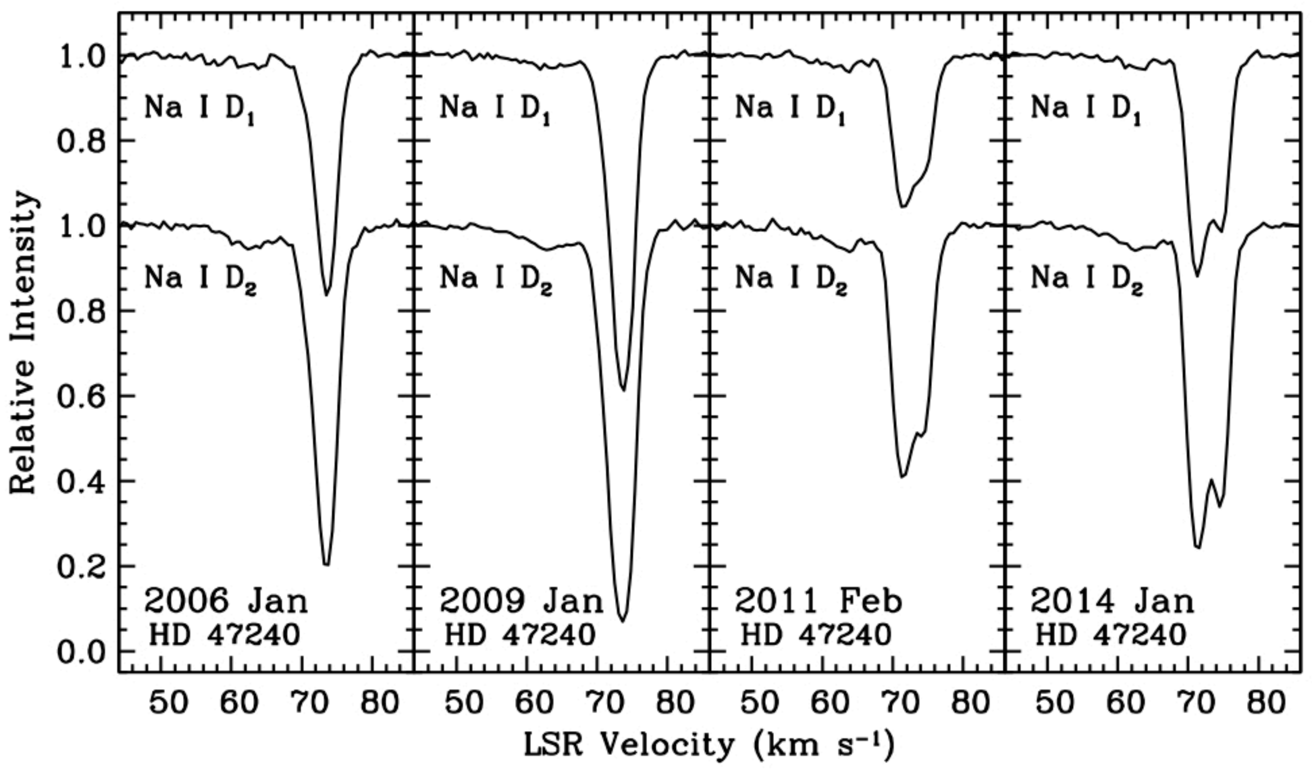
Over the past 10 years, we have obtained multi-epoch, high S/N, high-resolution (R≈230,000) observations of the interstellar Na I D absorption toward a sample of 20 stars with the KPNO Coude Feed telescope. Such observations take advantage of the tiny (≈0.0001″) absorption-line "beam" and the star/cloud proper motions to probe the structure of the intervening diffuse gas down to AU scales. The main goal of this survey is to search for temporal line-profile variations indicative of AU-scale Na I structure in a sample of diffuse ISM environments that include supernova remnants, H I shells, and stellar bow shocks. It constitutes the most sensitive long-term multi-epoch study of Na I to date in a variety of sightlines with the same instrumentation. Prior to this work, 15% of the ≈50 stars with published multi-epoch Na I observations have shown evidence of Na I structure on scales <50 AU (Crawford 2003; Lauroesch 2007).

Monoceros Loop

The most dramatic Na I variations among our sampled sightlines have been found in high-velocity gas associated with the Mon Loop (a ≈100,000 yr-old supernova remnant) toward the star HD 47240.



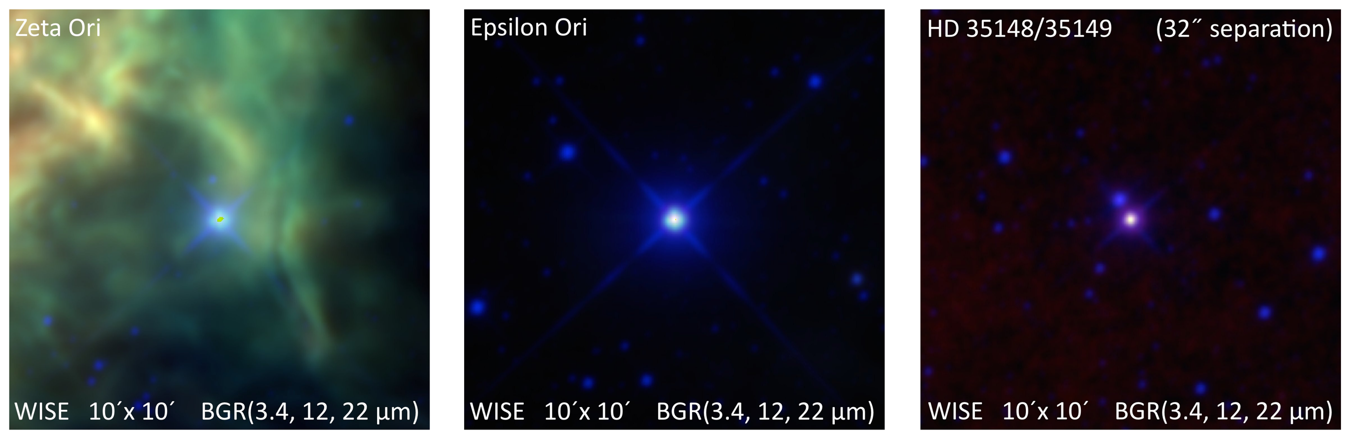
As illustrated in this DSS1 image, HD 47240 (d≈2 kpc) lies behind the southern edge of the 4˚ wide (100 pc at d≈1.6 kpc) Mon Loop. The Loop is expanding at a velocity of 50 km s^{-1} and is apparently interacting with the Rosette Nebula (the red region on the western edge of the DSS1 image) (Xiao & Zhu 2012).



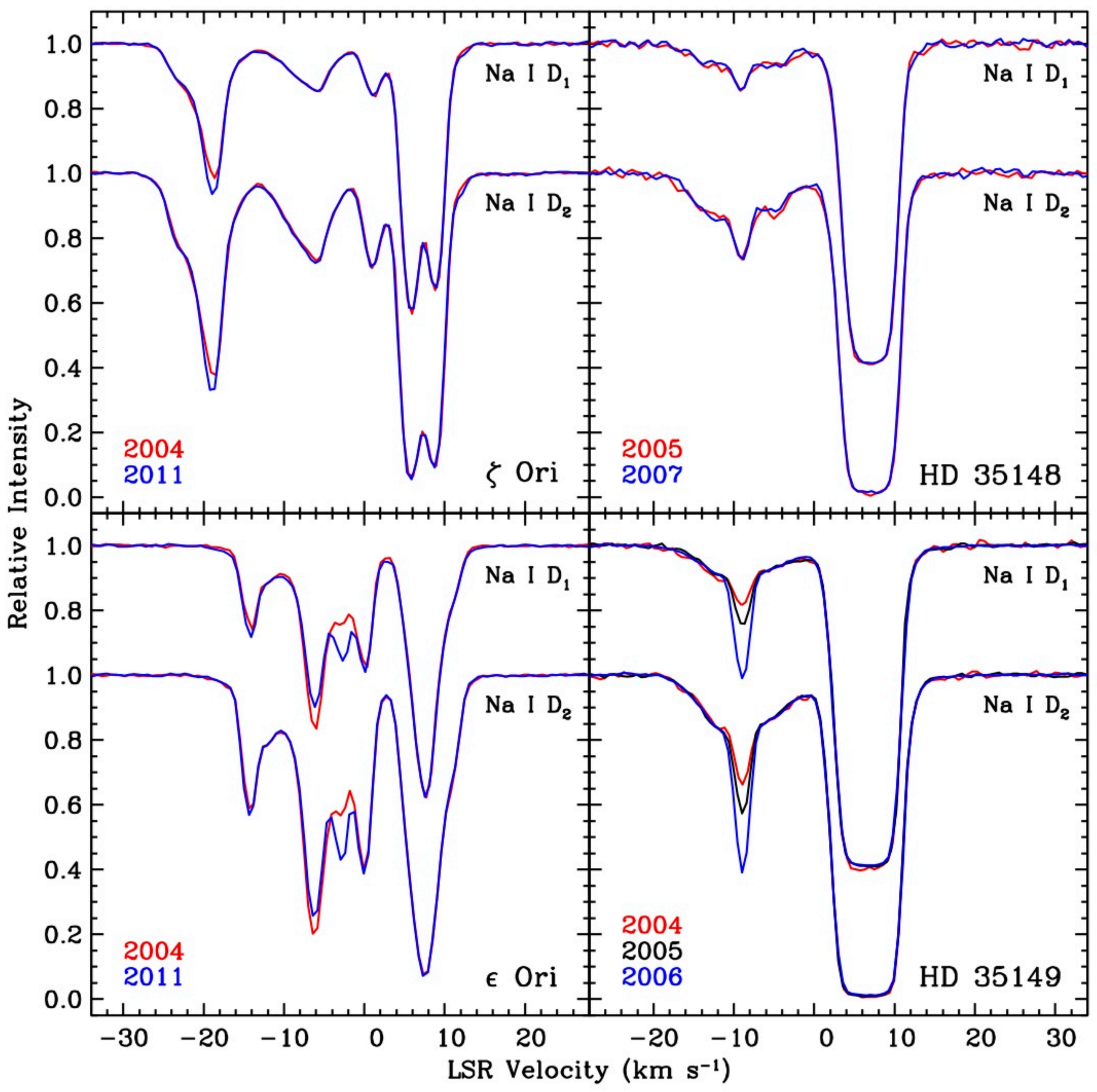
The high-velocity Na I absorption toward HD 47240 was discovered by Wallerstein & Jacobsen (1976). We find that this feature is well fit by a profile consisting of a weak, broad constant component at $v(LSR)$=+63 km s^{-1} and two narrow components of varying strength and separation centered near $v(LSR)$=+73 km s^{-1}. Between 2009 and 2011, the velocity separation of the narrow components increased from 0.6 to 3.0 km s^{-1} and their Na I column densities both declined by over 50%. As shown above, the high-velocity Na I absorption toward HD 47240 has been oscillating in strength for at least the past 8 years with a widening narrow-component separation now at 3.3 km s^{-1}. Given the 1.3 mas yr^{-1} proper motion of HD 47240 and the 50 km s^{-1} Mon Loop expansion velocity, these high-velocity absorption variations are sampling the structure of Na I clouds in the Loop over a transverse distance scale of ≈10 AU yr^{-1}.

Orion-Eridanus Superbubble

The Ori-Eri superbubble covers a 20˚x 40˚ sky region and has been shaped by stellar winds and supernovae from generations of high mass stars produced in the nearby (d≈400 pc) Orion star formation region (Reynolds & Ogden 1979; Bally 2008). Our sightline sample includes 10 stars in this region and 7 of them exhibited temporal variations in their interstellar Na I absorption during the 2004-2014 timeframe. Notable cases include the bright Orion Belt stars ζ Ori and ε Ori and the HD 35148/35149 (23 Ori) double star system.



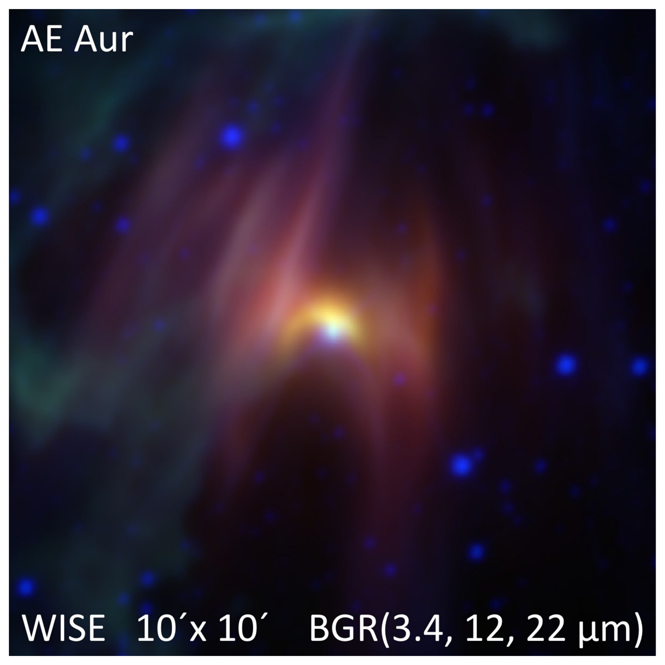
As shown above, the WISE close-up IR images of these 3 star fields show no obvious evidence of stellar bow-shock interactions with the surrounding ISM. ζ Ori and ε Ori are separated by 1.4˚ on the sky and HD 35148/35149 is located 5.8˚ NW of ε Ori.

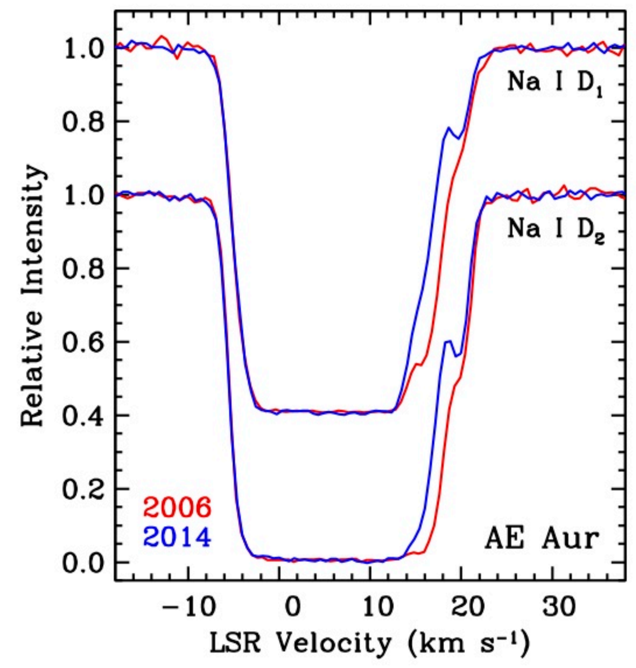


Many of the stars in the Ori-Eri region show multiple closely-spaced velocity components of interstellar Na I like ζ Ori and ε Ori above. In the case of ε Ori, we see that the adjacent Na I components at v(LSR)=-6 and -3 km s^{-1} decreased and increased respectively in strength between 2004 and 2011. Given the distance (≈600 pc) and proper motion (1.6 mas yr^{-1}) of ε Ori, these variations correspond to Na I structure on scales of ≈10 AU in the intervening clouds. In the case of HD 35148/35149 (separated by 0.08 pc at d≈500 pc), a Na I component at v(LSR)=-9 km s^{-1} is present in both spectra but varies dramatically toward HD 35149 over a 2 year period while remaining constant in strength toward HD 35148. Given the proper motion of HD 35149 (1.6 mas yr^{-1}), the fourfold Na I column density increase at v(LSR)=-9 km s^{-1} in this sightline from 2004 to 2006 occurred on a length scale of only ≈1.6 AU. Even allowing for a transverse gas flow up to 40 km s^{-1} relative to the star, the scale of this N(Na I) variation is still no more than 17 AU. Notably, this Na I component is totally absent in a 1996 spectrum of HD 35149 (Welty et al. 1999).

AE Aurigae

The runaway O-type star AE Aur (v(LSR)=+48 km s^{-1}) is well-known for its remarkable IR bow shock seen with IRAS, Spitzer, and WISE (van Buren & McCray 1988; Peri et al. 2012) as it interacts with the Flaming Star Nebula (IC 405). Our Na I observations of AE Aur have revealed a large variation in the red-most component of its heavily-saturated interstellar Na I absorption between 2006 and 2014.





Given the distance (≈550 pc) and proper motion (43.9 mas yr^{-1}) of AE Aur, this temporal variation corresponds to Na I structure on a scale of ≈200 AU if the absorbing cloud is near AE Aur. Numerical simulations (Comeron & Kaper 1998) have shown that bow shocks can generate small-scale pockets of dense, cool gas in their wake.

Commentary

Overall, twelve (HD 28497, HD 32039, HD 32040, ζ Ori, ε Ori, ι Ori, HD 35149, AE Aur, HD 47240, HD 84937, ρ Leo, and ζ Oph) of the twenty sightlines in our sample (also includes γ Cas, ζ Per, δ Per, δ Ori, κ Ori, HD 35148, β[1] Sco, and HD 157787) exhibited temporal variations in their interstellar Na I absorption during the past 10 years. Almost all of these twelve sightlines are associated with known supernova remnants, H I shells, or stellar bow shocks. Since Na I is not a dominant ion in diffuse interstellar clouds, temporal variations in its absorption along a particular sightline can be due to AU-scale fluctuations in either the total gas column N(H) or environmental conditions such as the cloud density n(H). Previous studies of UV interstellar lines have found that temporal dominant-ion absorption variations are exceedingly rare (Lauroesch 2007). As discussed by Lauroesch & Meyer (2003), a pattern of dominant-ion constancy and trace-neutral variability can be understood in terms of small-scale H I density fluctuations where species such as Na I are biased by the recombination rates to form on the H I density peaks within a cloud. Thus, it is most likely that the Na I variations reported here are due to AU-scale density fluctuations within the intervening clouds stimulated by turbulence (Audit & Hennebelle 2005) or converging gas flows (Vazquez-Semadeni et al. 2006). Our new results suggest that AU-scale density structure in the diffuse ISM may be more common than previously thought, particularly in complex regions such as the Ori-Eri superbubble that are being shaped by energetic gas flows driven by active star formation.

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Optical spectra obtained at KPNO, NOAO, which is operated by AURA, under cooperative agreement with the NSF. Archival IR images from WISE, a joint project of UCLA and JPL/CalTech funded by NASA. The red DSS1 archival image was digitally produced at STScI utilizing photographic data from the Palomar Observatory Sky Survey (CalTech/NGS).