A FUSE Survey of Interstellar Molecular Hydrogen
in the Small and Large Magellanic Clouds

Jason Tumlinson\textsuperscript{1}, J. Michael Shull\textsuperscript{1}, Brian L. Rachford\textsuperscript{1}, Matthew K. Browning\textsuperscript{1},
Theodore P. Snow\textsuperscript{1}, Alex W. Fullerton\textsuperscript{2}, Edward B. Jenkins\textsuperscript{3}, Paul A. Crowther\textsuperscript{4}, H. Warren Moos\textsuperscript{2}, Blair D. Savage\textsuperscript{5}, Kenneth R. Sembach\textsuperscript{6}, George Sonneborn\textsuperscript{7}, & Donald G. York\textsuperscript{8}

\textsuperscript{1} CASA, CB 389, University of Colorado, Boulder, CO, 80305 USA
\textsuperscript{2} Johns Hopkins University, USA
\textsuperscript{3} Princeton University Observatory, USA
\textsuperscript{4} University College London, UK
\textsuperscript{5} University of Wisconsin, Madison, USA
\textsuperscript{6} Space Telescope Science Institute, USA
\textsuperscript{7} GSFC/NASA, USA
\textsuperscript{8} University of Chicago, USA

We describe a moderate-resolution FUSE survey of H\textsubscript{2} along 70 sight lines to the Small and Large Magellanic Clouds, using hot stars as background sources. FUSE spectra of 67\% of observed Magellanic Cloud sources (52\% of LMC and 92\% of SMC) exhibit absorption lines from the H\textsubscript{2} Lyman
and Werner bands between 912 and 1120 Å. Our survey is sensitive to \( N(H_2) \geq 10^{14} \, \text{cm}^{-2} \); the highest column densities are \( \log N(H_2) = 19.9 \) in the LMC and 20.6 in the SMC. We find reduced \( H_2 \) abundances in the Magellanic Clouds relative to the Milky Way, with average molecular fractions \( \langle f_{H_2} \rangle = 0.010^{+0.005}_{-0.002} \) for the SMC and \( \langle f_{H_2} \rangle = 0.012^{+0.003}_{-0.002} \) for the LMC, compared with \( \langle f_{H_2} \rangle = 0.095 \) for the Galactic disk over a similar range of reddening. The dominant uncertainty in this measurement results from the systematic differences between 21 cm radio emission and Ly\( \alpha \) in pencil-beam sight lines as measures of \( N(HI) \). These results imply that the diffuse \( H_2 \) masses of the LMC and SMC are \( 8 \times 10^6 \, M_\odot \) and \( 2 \times 10^6 \, M_\odot \), respectively, 2% and 0.5% of the H I masses derived from 21 cm emission measurements. The LMC and SMC abundance patterns can be reproduced in ensembles of model clouds with a reduced \( H_2 \) formation rate coefficient, \( R \sim 3 \times 10^{-18} \, \text{cm}^3 \, \text{s}^{-1} \), and incident radiation fields ranging from 10 - 100 times the Galactic mean value. We find that these high-radiation, low-formation-rate models can also explain the enhanced \( N(4)/N(2) \) and \( N(5)/N(3) \) rotational excitation ratios in the Clouds. We use \( H_2 \) column densities in low rotational states \( (J = 0 \) and 1\) to derive kinetic and/or rotational temperatures of diffuse interstellar gas, and find that the distribution of rotational temperatures is similar to Galactic gas, with \( \langle T_01 \rangle = 82 \pm 21 \, \text{K} \) for clouds with \( N(H_2) \geq 10^{16.5} \, \text{cm}^{-2} \). There is only a weak correlation between detected \( H_2 \) and far-infrared fluxes as determined by IRAS, perhaps due to differences in the survey techniques. We find that the surface density of \( H_2 \) probed by our pencil-beam sight lines is far lower than that predicted from the surface brightness of dust in IRAS maps. We discuss the implications of this work for theories of star formation in low-metallicity environments.


For preprints, contact tumlinso@casa.colorado.edu
Also available from the URL http://casa.colorado.edu/~tumlinso/h2/

An Atlas of FUSE Sight Lines
Toward the Magellanic Clouds

Charles W. Danforth\(^1\), J. Christopher Howk\(^1\), Alex W. Fullerton\(^1,2\), William P. Blair\(^1\), Kenneth R. Sembach\(^1,3\)

\(^1\) Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA
\(^2\) University of Victoria, P. O. Box 3055, Victoria, BC V8W3P6, Canada
\(^3\) Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA

We present an atlas of 57 Large Magellanic Cloud (LMC) and 37 Small Magellanic Cloud (SMC) observations obtained with the Far Ultraviolet Spectroscopic Explorer satellite. The atlas highlights fifteen interstellar absorption line transitions at a resolution of \( \sim 15 \, \text{km} \, \text{s}^{-1} \). These transitions cover a broad range of temperatures, ionization states, and abundances. The species included are O\( \text{VI} \), which probes hot \( (T \sim 3 \times 10^5 \, \text{K}) \) ionized gas; C\( \text{II} \) and Fe\( \text{III} \), which probe warm \( (T \sim 10^4 \, \text{K}) \) ionized gas; Si\( \text{II} \), P\( \text{II} \), C\( \text{II} \), Fe\( \text{II} \), and O\( \text{I} \), warm neutral gas; and six different molecular hydrogen transitions, which trace cold \( (T \leq 500 \, \text{K}) \) gas. We include Schmidt H\( \alpha \) CCD images of the region surrounding each sight line showing the morphology of warm ionized gas in the vicinity, along with continuum images near each FUSE aperture position.

We present several initial scientific results derived from this dataset on the interstellar medium of the Magellanic Clouds and Galactic halo. O\( \text{VI} \) absorption at Magellanic Cloud velocities appears along nearly all sight lines, regardless of optical emission-line morphology. The velocity field of LMC disk
material is probed using P II λ1152.8 absorption and is seen to be consistent with recent H I results. While the velocity structure of the SMC is complex, two absorption features are clearly separated in the SMC data—a strong absorption complex between +100 and +130 km s$^{-1}$, and a weaker feature near +180 km s$^{-1}$. The velocity separation between these complexes varies with position, being greater on average in the southwest portion of the SMC. A lower-velocity absorption component seen the nine sight lines toward the bright H II region N66 in the SMC may be the result of an outflow or an old SNR within this nebular complex. Absorption in Fe II and O I at $\sim+60$ km s$^{-1}$ and $\sim+120$ km s$^{-1}$ appear along many LMC sight lines. They are attributed, respectively, to an intermediate velocity cloud and a high velocity cloud in the Milky Way halo. Both features are dramatically stronger toward the eastern half of the LMC and are not correlated with each other or with LMC Hα morphology. The lower velocity of the SMC and broader absorption lines complicate the detection of intermediate and high velocity Galactic absorption along SMC sight lines.

Submitted to: The Astrophysical Journal Supplement
For preprints, contact danforth@pha.jhu.edu
Also available from the URL http://www.pha.jhu.edu/~danforth/atlas/

H$_2$, HD, and CO at the edge of 30 Dor in the LMC:
the line of sight to Sk-69 246

H. Bluhm$^1$ and K.S. de Boer$^1$

$^1$ Sternwarte, Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany

FUSE and IUE observations of Sk-69 246, a WN6 star to the north of 30 Dor, reveal the existence of LMC interstellar gas in at least 3 velocity components. In one of these components FUSE spectra show strong absorption by molecular hydrogen with a column density of log $N$(H$_2$) = 19.6. We investigate the physical conditions in this cloud, which is probably located near the H II region surrounding Sk-69 246. HD and CO with column densities of $\approx 13.9$ and 13.0, respectively, are detected. The $N$(CO)-to-$N$(H$_2$) ratio is consistent with values found in the Galaxy. From the population of the rotational levels of H$_2$ we derive a gas temperature of 72 K and a radiation field $U \approx 3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-3}$ at 1000 Å. The fractional abundance $f = 2N$(H$_2$)/[$N$(H I) + 2N(H$_2$)] $\approx 0.07$ is rather high for an $E(B-V) \leq 0.1$

Accepted by: Astronomy & Astrophysics
For preprints, contact hbluhm@astro.uni-bonn.de

3
Orbits of Four Very Massive Binaries in the R136 Cluster

Philip Massey¹, Laura R. Penny², and Julia Vukovich³

¹ Lowell Observatory, USA
² Department of Physics and Astronomy, College of Charleston, USA

We present radial velocity and photometry for four early-type, massive double-lined spectroscopic binaries in the R136 cluster. Three of these systems are eclipsing, allowing orbital inclinations to be determined. One of these systems, R136-38 (O3 V + O6 V), has one of the highest masses ever measured, $57M_\odot$, for the primary. Comparison of our masses with those derived from standard evolutionary tracks shows excellent agreement. We also identify five other light variables in the R136 cluster which are worthy of follow-up study.

Accepted by: The Astrophysical Journal
Preprints from ftp://ftp.lowell.edu/pub/massey/r136bins.ps.gz

Blue irregular variable stars in the Small Magellanic Cloud from EROS2 : Herbig Ae/Be or classical Be stars?

J.-P. Beaulieu¹, W.J. de Wit²,³, H.J.G.L.M. Lamers²,³, J.-B. Marquette¹, C. Coutures⁴, P. Leisy⁵, S. Totor¹, N. Palanque-Delabrouille⁴, C. Afonso⁴, et al., (EROS2 collaboration)

¹ Institut d’Astrophysique de Paris, 98 bis Boulevard Arago, 75014 Paris, France
² Astronomical Institute, University of Utrecht, Princetonplein 5, NL-3584 CC, Utrecht, The Netherlands
³ SRON Laboratory for Space Research, Sorbonnelaan 2, NL-3584 CA, Utrecht, The Netherlands
⁴ CEA, DSM, DAPNIA, Centre d’Etudes de Saclay, 91191 Gif sur Yvette, Cedex, France
⁵ ESO La Silla, casilla 19001, Santiago 19, Chile

Using data from the EROS2 microlensing survey, we report the discovery of two blue objects with irregular photometric behaviour of $\Delta V \sim 0.1$-0.4 mag on time scales of 20 to 200 days. They show a bluer when fainter behaviour. Subsequent spectra taken with the ESO 3.6m telescope show spectral type B4dII and B2dV-V with strong Hα emission. These objects resemble the Herbig AeBe but also classical Be stars.

At this stage, it is not possible to distinguish unambiguously between pre-main sequence and classical Be nature. If we favour the pre-main sequence interpretation, they are more luminous than the luminosity upper limit for Galactic HAEBe stars. The same was found for the HAEBe candidates in the LMC. This might be due to a shorter accretion time scale ($\tau = M_*/\dot{M}$), or the smaller dust content during the pre-main sequence evolution of SMC and LMC stars. Further studies on a larger scale of the environment, and IR properties of the stars are needed.

Accepted by: Astronomy and Astrophysics
For preprints, contact beaulieu@iap.fr
Also available from the URL http://xxx.lanl.gov/abs/astro-ph/0110166
Search for second overtone mode Cepheids in Magellanic Clouds
II. Characteristics of second overtone mode pulsations

E. Antonello¹, D. Fugazza¹ and L. Mantegazza¹
¹ Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate, Italy

The analysis of CCD observations of ten new suspected second overtone mode Cepheids in the SMC do not confirm the nature of such stars; most of them appear to be first overtone mode Cepheids. A careful analysis of the OGLE best second overtone mode candidates and of the second overtone component of double mode Cepheids in SMC and LMC has been performed in order to clarify the possible effects of a resonance between pulsation modes. There are some indications that such a resonance is indeed operating in these pulsators.

Submitted to: Astronomy & Astrophysics
For preprints, contact elio@merate.mi.astro.it

Abstracts of Non-Refereed Papers

Interstellar Abundances in the Magellanic Clouds

Daniel E. Welty¹
¹ University of Chicago, AAC, 5640 S. Ellis Ave., Chicago, IL 60637, USA

We summarize recent studies of the predominantly neutral gas in the Magellanic Clouds (MC), based on combinations of high-resolution optical spectra and UV spectra obtained with *IUE*, *HST*, and *FUSE*. Similarities in relative gas-phase abundances for Galactic and MC sightlines with relatively low *N(H)* had suggested that the depletion patterns might be similar in the three galaxies — at least where the depletions are relatively mild. New STIS spectra of one higher *N(H)* SMC sightline, however, have revealed significant differences, relative to the Galactic patterns, for SMC clouds characterized by more severe depletions.

To appear in: IAP XVIIth Colloquium — Gaseous Matter in Galaxies and Inter-galactic Space (Paris; 2001 June)
For preprints, contact welty@oddjob.uchicago.edu
Also available from the URL ftp://astro.uchicago.edu/pub/astro/welty/IAP17/weltytalk.ps.gz
Interstellar O vi in the Large Magellanic Cloud

J. Christopher Howk

1 Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA

I summarize Far Ultraviolet Spectroscopic Explorer (FUSE) observations of interstellar O vi absorption towards 12 early-type stars in the Large Magellanic Cloud (LMC), the closest disk galaxy to the Milky Way. LMC O vi is seen towards all 12 stars with properties (average column densities, kinematics) very similar to those of the Milky Way halo, even though O/H in the LMC is lower by a factor of ~ 2.5. Sight lines projected onto known LMC superbubbles show little enhancement in O vi column density compared to sight lines towards quiescent regions of the LMC. The O vi absorption is displaced by ~ −30 km s\(^{-1}\) from the corresponding low-ionization absorption associated with the bulk of the LMC gas. The LMC O vi most likely arises in a vertically-extended distribution, and I discuss the measurements in the context of a halo composed of radiatively-cooling hot gas. In this case, the mass-flow rate from one side of the LMC disk is of the order \( M \sim 1 \, M_\odot \, \text{yr}^{-1} \).

To appear in: Proceedings of the XVIIth IAP Colloquium: Gaseous Matter in Galactic and Intergalactic Space
For preprints, contact howk@pha.jhu.edu
Also available from the URL http://fuse.pha.jhu.edu/~howk/Papers/

The Galactic Halo UV Field, Magellanic Stream and HVCs

J. Bland-Hawthorn\(^1\) & M.E. Putman\(^2\)

1 Anglo-Australian Observatory, PO Box 296, Epping, NSW, Australia
2 Australia Telescope National Facility, PO Box 76, Epping, NSW, Australia

Significant numbers of high-velocity H\(_i\) clouds (HVCs) have now been detected in H\(_\alpha\), with a subset seen in low ionization lines (e.g. [NII]). It was originally hoped that the observed H\(_\alpha\) strength would provide a distance constraint to individual clouds. This idea requires that a useful fraction (\( f_{\text{esc}} > 1\% \)) of ionizing photons escape the Galaxy, and that the halo ionizing field is relatively smooth, as we discuss. HVCs which are known to be close to the Sun are H\(_\alpha\)-bright; the brightest clouds also show enhanced [NII] emission, in contrast to the Magellanic Stream where the low ionization emission lines are always weak compared to H\(_\alpha\). But an acute complication for H\(_\alpha\) distances is the apparent H\(_\alpha\) brightness of the Magellanic Stream along several sight lines, comparable or brighter than local HVCs. To account for this, we present three possible configurations for the Magellanic Stream and propose a follow-up experiment. If we normalize the distances to local HVCs, some HVCs appear to be scattered throughout the Galactic halo on scales of tens of kiloparsecs.

Also available from the URL http://xxx.lanl.gov/abs/astro-ph/0110043
**Hα Distance Constraints for High Velocity Clouds in the Galactic Halo**

J. Bland-Hawthorn\(^1\) & P.R. Maloney\(^2\)

1 Anglo-Australian Observatory, PO Box 296, Epping, NSW, Australia
2 Center for Astrophysics & Space Astronomy, University of Colorado, Boulder, CO 80309-0389, USA

We present some developments in determining Hα distances to high-velocity clouds (HVCs) in the Galactic halo. Until recently, it was difficult to assess the nature and origin of HVCs because so little was known about them. But now several HVCs have reliable distance bounds derived from the stellar absorption technique, and more than a dozen have abundance measurements. In addition, twenty or more HVCs have been detected in Hα (and a few in optical forbidden lines). Over the past five years, we have been developing a model of the halo radiation field which includes contributions from the stellar disk, the stellar bulge, the hot corona, and the Magellanic Clouds.\(^1\) In certain instances, the Hα flux from an opaque Hi cloud can be used to derive a crude distance constraint to the cloud. For a UV escape fraction of \(f_{\text{esc}} \approx 6\%\) perpendicular to the disk (\(f_{\text{esc}} \approx 1 - 2\%\) when averaged over solid angle), the HVCs appear to be broadly consistent with the spiral arm model. We caution that a larger database with full sky coverage is required before the usefulness of Hα distances can be fully assessed. We present a number of detailed predictions from our distance frame to encourage independent assessments from future observations. If the model is valid, we find that most HVCs detected to date are scattered throughout the halo up to distances of 50 kpc from the Sun. Most of this material is likely to be debris from recent galaxy interactions, or even debris dislodged from the outer Galaxy disk. We propose some future tests of the Hα distance model and briefly discuss recent Hα detections along the Magellanic Bridge and Magellanic Stream.

**To appear in:** Extragalactic Gas at Low Redshift, ASP Conf. Series, eds. J. Mulchaey & J. Stocke

**The Pillars of the Second Generation**

Nolan R. Walborn\(^1\)

1 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

The ubiquitous triggered, second-generation star formation around the peripheries of massive young clusters is reviewed. Frequently, the most luminous second-generation sources are located at the heads of dust pillars oriented toward the central cluster. Recent HST WFPC2 and NICMOS observations of 30 Doradus are emphasized, but a number of other regions exhibiting the phenomenon are also discussed, including the Galactic 30 Dor counterpart NGC 3603. The next evolutionary phase of such objects is the giant shell H II region, as epitomized by N11 in the LMC, NGC 604 in M33, and NGC 4214 I-A. Detailed information about the nearby objects provides valuable insights for the interpretation of more distant starbursts.


For preprints, contact walborn@stsci.edu

---

\(^1\)The disk\(h\)alo ionization code, along with full documentation (Bland-Hawthorn & Maloney 2001), is to be made available for general use.
Pulsating AGB stars in the LMC

Jacco Th. van Loon

Astrophysics Group, School of Chemistry & Physics, Keele University, Staffordshire ST5 5BG, United Kingdom

I give a brief review and interpretation of the evolution, mass loss and pulsation of AGB stars in the Large Magellanic Cloud.

For preprints, contact jacco@astro.keele.ac.uk

Cross–matching DENIS and 2MASS Point Sources towards the Magellanic Clouds

N. Delmotte¹, D. Egret¹, C. Loup² and M.-R. Cioni³
¹ CDS, Observatoire Astronomique de Strasbourg, UMR 7550, 11 rue de l’Université, 67000 Strasbourg, France
² Institut d’Astrophysique de Paris, CNRS, 98 bis Bd Arago, 75014 Paris, France
³ Leiden Observatory, University of Leiden, P.O. Box 9513, 2300 RA Leiden, The Netherlands

The recent publications of the DENIS Catalogue towards the Magellanic Clouds (MCs) with more than 1.3 million sources identified in at least two of the three DENIS filters (I J Ks) and of the incremental releases of the 2MASS point source catalogues (J H Ks) covering the same region of the sky, provide an unprecedented wealth of data related to stellar populations in the MCs. In order to build a reference catalogue of stars towards the Magellanic Clouds, we have performed a cross–identification of these two catalogues. This implied developing new tools for cross–identification and data mining. This study is partly supported by the Astrovirtel program that aims at improving access to astronomical archives as virtual telescopes. The main goal of the present study is to validate new cross–matching procedures for very large catalogues, and to derive results concerning the astrometric and photometric accuracy of these catalogues. The cross–matching of large surveys is an essential tool to improve our understanding of their specific contents. This approach can be considered as a new step towards a Virtual Observatory.

For preprints, contact delmotte@astro.u-strasbg.fr
Also available from the URL http://astro.u-strasbg.fr/~delmotte/HC2/
Cepheids as Distance Indicators: Some Current Problems

Michael Feast

A general review is given of the calibration of the Cepheid distance scale, with particular reference to its use in the determination of $H_0$. Emphasis is placed on the advantage of using a galactic calibration of the Cepheid scale, rather than relying on an adopted distance of the LMC. It is then possible to use LMC data to test for possible metallicity effects on this scale.


For preprints, contact mwf@artemisia.ast.uct.ac.za
Also available from the URL http://xxx.lanl.gov/abs/astro-ph/0110360