Discipline Working Group on UV Astronomy (Spectroscopy)

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FINAL REPORT

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Executive summary :

The objective of the DWG on ultraviolet (UV) astronomy is to promote the continued development of UV space astronomy in Canada, and in particular UV spectroscopy. The UV region (110 – 320 nm), which is only accessible from space, is extraordinarily rich in spectroscopic diagnostics of the plasmas found in a wide variety of astronomical objects and environments. The ultraviolet spectral domain remains one of the most important Windows to the Universe, in which Canadian scientific expertise is widely recognized.

However, it is profoundly disturbing that there are no credible plans to maintain access to this astrophysically crucial window to the Universe beyond the May 2009 Servicing mission to the Hubble Space Telescope. Since no other national space agency is currently building a UV telescope with spectroscopic capabilities, the DWG explored ways of using Canadian expertise, both in academia and the industry, to maintain access to this crucial waveband. While the closing of the UV window to high-resolution spectroscopy represents a looming disaster for quantitative astrophysical analysis by astronomers world-wide, it also becomes a tremendous opportunity for the Canadian astronomical community and the CSA to become true leaders in space astronomy.

The DWG has identified five key science areas that define the design of a future spectroscopic UV observatory, namely : (1) Wind and mass-loss properties of hot, massive stars; (2) Chromospheric activity and mass loss in cool stars; (3) Precise determination of stellar masses in binaries; (4) The evolution of starburst galaxies; (5) The variability of active galactic nuclei. Because of substantial improvements in detector technology over the past years, significant breakthroughs in these topics can be reached with a well-designed, modest-size, dedicated space telescope.

The DWG has explored two paths to reach the above-mentioned objectives, namely the development of a Canadian UV spectroscopic satellite and the participation in a large, multi-purpose, international telescope.

In order to fully benefit from the academic and industrial expertise now available in Canada, the DWG recommends that conceptual studies of a modest-size (0.5 – 1.0-m primary mirror) telescope equipped with a dual resolution spectrograph be undertaken. Leadership through the UV « Dark Age » will take the Canadian space astronomy community to new heights of credibility.

1 - Meetings Held and Attended

- CASCA 2007 (2007 June 5 – 8; RMC, Kingston); presentation on « High-Resolution UV Spectroscopy : A Target of Opportunity for Canadian Space Astronomy » during the special session on « Future Space Astronomy Missions » (Drissen, Fullerton, Hall, Hutchings, Moffat, Rowlands).
- Astrosat/UVIT Science Planning (2007 October)
- « Future Directions in UV Spectrocopy » (2008 Oct. 20-22; Annapolis, MD) » [Fullerton]
- « Beyond JWST : The Next Steps in UV-Optical-NIR Space Astronomy » (2009 March 26-27; STScI, Baltimore, MD) [Bennett, Fullerton]
- We also held numerous teleconferences during the preparation of the CUVIT document.

2 - Key science objectives

From an astrophysical point of view, the ultraviolet (UV) region (90 – 320 nm) is particularly rich in atomic and molecular transitions, and covers the region in which the intrinsic spectral distribution of hot stars, starburst galaxies and active galactic nuclei peak. In particular, electronic transitions from ground and low-lying metastable levels of astrophysically abundant elements and ions, and the important molecular species of CO and H_2, appear, with only very few exceptions, in the ultraviolet spectrum. These are lines which are least influenced by non-LTE effects in stellar photospheres and are thus most useful for quantitative abundance determinations. The lower levels of these lines are least likely to depopulate in low density environments such as chromospheres, circumstellar shells, stellar winds, nebulae and the interstellar medium, and so remain the only useful diagnostics in most of these environments. Another advantage of observing in the ultraviolet is the extreme sensitivity of the Planck function to the presence of small amounts of hot gas in dominantly cool environments. This allows the detection and monitoring of various phenomena that would otherwise be difficult to observe: accretion continua in young (T Tauri) stars, magnetic activity, chromospheric heating, and starspots on cool stars, and intrinsically faint, but hot, companions of cool stars.

The Earth's atmosphere is opaque to most of the electromagnetic spectrum, with the exception of narrow windows in the visible (330 nm to 950 nm), the near infrared (950 nm to 5 μm) and radio wavebands. Gamma rays, X rays and the UV regime, emitted by the hottest and most energetic objects in the Universe, are therefore only accessible from space. Since the late 1960s, astronomers all over the world have had access to ultraviolet telescopes: Copernicus (1972 – 1981), the International Ultraviolet Explorer (IUE; 1978 – 1996), the Hubble Space Telescope (1990 – 2015?) and the Far Ultraviolet Spectroscopic Explorer (FUSE;1999 – 2007) to name just a few. Within a very few years however, and continuing for another decade or so, there will be no operational space mission with ultraviolet spectroscopic capability. Yet, the ultraviolet spectral domain remains one of the most important windows to the Universe, in which Canadian scientific expertise is widely recognized.

The global scientific themes presented below – namely the study of the fundamental properties of stars across the Hertzsprung-Russell diagram and the evolution of galaxies – are key components of the Long Range Plan (Sections 2.1 and 2.4) for Canadian astronomy ("The Origins of Structure in the Universe") prepared by the Canadian Astronomical Society (CASCA).

The science drivers presented below reflect the main interests of the members of the DWG. But as every new telescope project has shown, the technical capabilities dictated by the few initial science objectives are also well suited to a wide range of other projects. The Hubble space telescope is a vibrant testimony to this approach. We feel however that a mission will be much more productive if a small selection of science projects with strong key questions are selected and if the telescope is fully dedicated to answer these questions. This often requires the observation of large sample of targets, or repeated observations of the most representative objects, as exemplified in the following sections. This type of science can be performed much more efficiently by a small, dedicated telescope than by a large-aperture, general-purpose observatory; this has been demonstrated on the ground and in space. The extremely successful Canadian-led MOST mission (Matthews, 2006, IAUJD, 17, 21) is a superb example of the quality of science that can follow from this kind of focussed approach.

2.1 - Hot, massive stars

The golden age of UV astronomy, started in the late 1960s, has taught us that massive stars, those with an initial mass larger than 10 $M_\odot$ (solar masses) and which end their life as supernovae, have a major impact on their surroundings and the evolution of galaxies. Because these stars are very hot and luminous, they emit most of their flux in the UV, which ionizes the interstellar medium (ISM) out to very large distances. Their powerful winds also inject huge amounts of mechanical energy and heavy elements into the ISM, particularly during their late stages of evolution and subsequent explosion as core-collapse supernova. Massive stars have thus been important actors in galactic and cosmic evolution since the Big Bang; analysis of their properties has implications in areas as diverse as the kinematics of the ISM, the origin of gamma-ray bursts, the chemical evolution of galaxies and the reionization of the early Universe.

The UV resonance lines of multiply ionized metals – particularly O VI λλ1032, 1037; P V λλ1118, 1128; N V λλ1234, 1238; Si IV λλ1398, 1402; C IV λλ1548,1550 (all wavelengths in Å) - are sensitive tracers of circumstellar material. They are the pre-eminent diagnostics of the massive outflows from early-type (i.e., O, B, and Wolf-Rayet stars) and define the most important wavelength range for the study of massive stars. Through careful modelling of the shapes of line profiles, the radial distributions of density, ionization, and velocity can be determined. Despite a generation of intensive studies, none of these fundamental parameters are known with sufficient accuracy to provide reliable determinations of the mass-loss rate. Consequently, the mass flux from these stars is still uncertain, which limits models for the evolution of massive stars and the "feedback" of energy and material they provide to their local interstellar environments. A steady stream of high-quality UV spectra is required to test and extend modern model atmosphere programs, which form the basis for quantitative understanding of these processes. In particular, UV spectra are essential to solve the following problems:

- <u>The time-dependent structure of the stellar wind.</u> The origin of the variability and its implication for the structure of the stellar wind remain mysterious. The problem can only be addressed by enlarging the sample of stars that have been studied intensively (i.e., over a basline of weeks - months).

- <u>The mean structure of hot-star winds</u>. Recent work suggests that the winds of most (probably all) early-type stars are highly inhomogenous. The origin of this structure is likely connected to the variability noted above, but its influence on various diagnostics of the wind is currently a matter of intense study. High-quality measurements of line profiles are required to provide meaningful constraints on models that aim to describe the porosity of stellar winds.

- Fundamental stellar parameters. Modern model atmosphere programs, which treat the stellar photosphere and the expanding wind in a unified, self consistent manner, can be used to constrain the chemical composition of hot, massive stars. This is particularly true for metallic species (represented by the dominant resonance lines formed in the wind), which generally do not have accessible transitions in the optical region of the spectrum.

- Colliding winds in binary systems. Both components in an early-type binary system have a powerful stellar wind. The collision of these winds perturbs the circumstellar environment, and provides unique diagnostic information about the relative momentum carried by each outflow. These interactions are best studied via long-term monitoring of UV wind profiles.

- Mass loss and evolution as a function of stellar metallicity. The early-type stars in the Large and Small Magellanic Clouds provide superb testbeds for theoretical predictions of the effect of mass loss on the evolution of early-type stars. Although HST and FUSE have provided a valuable reconnaissance of the early-type stars in the Magellanic Clouds, the sample size remains small. Further high S/N observations are required to enlarge the samples so that statistically meaningful conclusions can be drawn. Some dense fields in the Magellanic Clouds are rich enough in massive stars to justify the use of a multi-object spectrograph (MOS) capability.

2.2 - Solar-type and other cool stars

It seems paradoxical to study cool stars in a spectral region where their continuum flux is relatively low, but for many applications observation of their ultraviolet spectrum remains crucial. Indeed, the flux contrast between emission from hot sources in predominantly cooler environments is greatly enhanced in the ultraviolet compared to the optical region accessible from the ground. For example, observations of the chromospheric spectrum (and stellar activity) in cool stars are straightforward in the UV because the key diagnostics dominate the ultraviolet spectrum (which is not the case in the optical spectrum). Since characterization of extrasolar planets will increasingly drive astronomical research, we foresee the need for detailed modelling of the atmospheres of their host stars (typically F-, G-, or K-stars), and detailed monitoring of the host's stellar activity cycles. This work is most reliably and readily accomplished via UV spectroscopy, and will be a key investigative niche for an all-Canadian satellite.

By far the easiest and most robust way to monitor stellar activity by observations of strong chromospheric lines such as the Mg II h and k resonance lines near 2800 A, and the C IV resonance doublet near 1550 A. Both are in the ultraviolet inaccessible from the ground, and must be observed from space. Although ground-based observations of solar-type stars are possible, and have by carried out for many years by the Mt. Wilson H-K Project, using the Ca II H and K resonance doublet (Baliunas et al. 1995, ApJ 438, 269), and more recently at Lowell Observatory (Hall, Lockwood & Skiff 2007, AJ 133, 862), this is a difficult observation. For example, for the Sun, the Ca II chromospheric emission lines contain only a tiny fraction of the flux in this region, and appear as two weak self-absorbed emission features at the bottom of a strong photospheric line (cf. Livingston et al. 2007, ApJ 657, 1137). The flux in the photospheric line core is about

10% of the continuum, while the chromospheric emission peaks being measured have an amplitude of just 1% of the continuum. These difficulties are entirely avoided at Mg II and C IV, where the chromospheric emission fluxes completely dominate the continuum spectrum (because the continuum spectrum is much fainter in the UV, and the chromospheric diagnostic lines are intrinsically stronger). Furthermore, monitoring the entire UV spectrum yields fluxes from a range of chromospheric lines of various excitation which better constrains the construction of semi-empirical models.

This research is of interest well beyond the astronomical community because of the links between solar activity and climate: solar activity is widely believed to have a small, but significant affect on Earth's climate, in the sense that a more active Sun implies a warmer Earth. Two mechanisms have been suggested: (1) an increase in solar UV luminosity with stellar activity, and (2) a decrease in mean terrestrial cloud cover due to decreased cosmic ray background during periods of increased stellar activity (because the stronger solar wind magnetic field reduces the incident cosmic ray flux at the Earth). The first effect is small: a change in total solar luminosity of about 0.1% from cycle minimum to maximum (Foukal et al. 2006, Nature, 443, 161), and the second effect (Svensmark 2007, A&G 48, 18) is controversial, especially in the climate science community. However, the cosmic ray/cloud cover mechanism has been proposed by Shaviv (2005, JGR, 110, 1029) as a way of avoiding the "snowball Earth" scenario (the totally glaciated Earth) which is inconsistent with the geologic record. The early Sun was about 30% less luminous than at present, but also 1-2 orders of magnitude more active (due to faster primordial rotation). A significant issue in the current global warming debate is the contribution from solar variability. Although almost all climate scientists believe anthropogenic effects dominate today, the solar variability contribution remains more uncertain than desired, especially since solar activity (and the implied solar contribution to climate warming) has been at a long term maximum for the past several decades. Quantifying the effects of stellar activity on climate is also of crucial importance for determining habitable zones around nearby solar-type stars.

In general, construction of model stellar atmospheres and chromospheres involves the comparison of theoretical profiles of atomic lines to observation, which requires high signal-to-noise (S/N) observations at high spectral resolution (R= 50,000 to 100,000). For spectral energy distribution work, photometric fluxes and complete spectral coverage are also required. An important consideration is that the proposed UV telescope must be able to observe bright, well-studied standard stars for this purpose.

2.3 - Mass loss from cool stars

Another major source of uncertainty inhibiting deeper understanding of the evolution of cool, massive stars (G-M bright giants and supergiants) is our present inability to model their mass loss in a fundamental way. Mass loss from these cool supergiants proceeds via a cool, low-velocity, massive wind that depletes the convective envelopes of these stars on an evolutionary timescale. This mass loss process is not understood, and for now, the only practical approach to modeling these winds is by the construction of semi-empirical wind models based on observation. There are no good diagnostics available in the optical spectrum; despite the weakness of the ultraviolet spectrum, the best diagnostics are still to be found there. Binaries can also be used here to good advantage because the (typically) B-type companions can supply orders of magnitude more photons than are available from the cool supergiants. A "chromospheric" absorption spectrum is superimposed on the hot companion's continuum as it shines through the chromosphere and wind of the cool supergiant, revealing information about the supergiant's wind along the line of sight. Another advantage of using binaries in this manner is that the chromospheric spectrum contains information about a region of the wind that is much smaller than the size of the (large) supergiant star. Typically, structure in the wind is resolved down to a size of 1-2% of the supergiant's radius. The method, and preliminary observations, is described for the M supergiant eclipsing binary VV Cephei by Bauer, Bennett & Brown (2007, ApJS 171, 249), and for the K supergiant binary 31 Cygni by Bennett (2006, ASPC, 348, 254). The results of the binary approach have been confirmed by VLA radio continuum observations (Harper et al. 2005, AJ, 129, 1018).

2.4 - Binary stars

The mass of a star is by far the most important parameter determining its evolution and fate, and with it the global evolution of galaxies. The only fundamental way to determine stellar masses are using binary star systems with known orbital parameters. But extremely few cool, evolved stars of intermediate and high mass (these are G-M bright giants and supergiants) have had masses determined in this way. The lack of an accurate mass calibration is reflected in the uncertainties in evolutionary model tracks of these stars. The main problem is that these binaries have been traditionally difficult observational targets. Typically, the companions of cool supergiants are B-type stars still on the main sequence. Periods are quite long: several years to decades, making them unattractive targets for most research programs. To determine masses, the radial velocity amplitudes of both orbits must be known. In the optical, the light is dominated by the cool supergiant primaries, for which measuring the radial velocity orbit is straightforward. However, the hot companion's spectrum is difficult to work with. First, it must be disentangled from the (optically) brighter supergiant. Even then, one is left with a nearly featureless spectrum except for the Stark-broadened Balmer lines, which are nearly useless for velocity determination. Measurements are much simpler in the ultraviolet. Here the hot star's spectrum dominates, and the spectrum (especially shortward of 200 nm) is rich with metal lines. In the UV, the determination of the companion's radial velocity orbit becomes routine (Bennett et al. 1996, ApJ 471, 454; Brown et al. 2001, AJ, 122, 392). Therefore, a program to monitor the ultraviolet spectrum a sample of binaries, especially eclipsing binaries for which a complete spectroscopic solution is possible, over a complete orbit could yield masses of G-M bright giants and supergiants accurate to 1-2%. This monitoring program would yield a well-determined set of primary standards, and lay the foundation for an improved mass calibration of cool giant and supergiant stars. The observational requirements are high S/N, high spectral resolution and wide spectral coverage (in order to observe many lines simultaneously).

2.5 - Starburst galaxies

Starbursts represent an ideal laboratory to study massive stars, star formation, and also the evolution of galaxies. Starbursts are sites of intense, violent and recent star formation that may not last for very long. The star formation rate may exceed by a factor of 10 to 100 the rate observed in a normal disk galaxy. Massive stars, with short lifetimes, are present in large number in starbursts and are dominate the observed flux in most wavebands. Massive stars, because of their high surface temperature, are prime contributors to the ultraviolet (UV) flux; in the presence of gas and dust, part of this UV flux is absorbed to produce nebular lines in the optical and near-infrared (IR), and thermal emission in the far-IR. Therefore, starbursts of all types -- nearby HII regions, HII galaxies, blue compact dwarf galaxies, nuclear starburst galaxies, IR-luminous galaxies, and star-forming galaxies at high redshift -- are observed.

The origin of a starburst is strongly related to the perturbation of the galaxy gas reservoir. A strong correlation between starbursts and tidal interaction or merger events is seen in many galaxies (e.g. Kennicutt et al. 1987, AJ 93, 1011). In isolated starburst galaxies, a gas perturbation is proposed to occur due to internal processes such as a bar instability (e.g. Combes 2000, PASP 230, 213) or to occur in relation with an active nucleus or to result from self-induced supernovae and stellar winds (e.g. Heckman 2003, RMAA 17, 47). UV images with the Hubble Space Telescope (HST), have shown star formation in the shape of multiple luminous bright knots on scales of 10-100 pc in starburst galaxies (Meurer et al. 1995, ApJ 110, 2665). This small-scale structure may imply that a single star-forming event propagates through a galaxy and shapes part (if not all) of its morphology. Nearby, we have examples of HII regions where a very young (~1 Myr) second generation of stars was triggered by a massive outflow from a slightly older central concentration of stars (e.g. 30 Dor, Walborn et al. 1999, AJ 117, 225).

Because of their massive stars, starbursts are important producers of mechanical energy, ionization flux, and metals in their host galaxy. Starbursts shape the morphology of galaxies throughout the universe and, therefore, are believed to represent an important phase in the evolution of galaxies. The starburst phenomenon constrains the parameters (mass, gas, metallicity, interaction, bars, etc.) which influence the star formation process. As such, it represents an important test for massive star formation theories.

With the launch of the Hubble Space Telescope in 1991, studies in the ultraviolet wavelength range have grown in number. Leitherer, Robert & Drissen (1992, ApJ 401, 596) have developed an evolutionary population synthesis code Starburst99 to study the UV spectrum for young stellar populations. The UV spectral range shows signatures from the massive stars, which are sensitive to their effective temperature, luminosity, and metallicity (e.g. SiIV and CIV). For example, strong P Cygni profiles are formed in the expanding envelope of supergiants. They are relatively free from contamination, unlike the visible where the photospheric lines from the massive stars are generally blended with nebular lines. A parallel version of the code, LavalSB was developed by Dionne & Robert (2006, ApJ 641, 252) and is optimized for the synthesis at four different metallicities. It also includes evolutionary tracks for massive close binaries. It reproduces the UV flux and lines based on a UV spectral libraries composed of medium-high resolution spectra of O, B, and WR stars observed with IUE, HST, and FUSE in the Galaxy and the Magellanic Clouds. It uses stellar evolutionary tracks to follow the individual stars as a function of the population age and metallicity. This stellar populations is first defined by an initial mass function and a star forming rate. At each time step, the integrated spectrum is created by summing the individual star contributions. The comparison with observations allows us to estimate the age, metallicity, star formation history of starbursts. The absolute UV flux synthesis gives the extinction, the number of massive stars, and the predicted flux at Hα, usually in good agreement with other studies.

The synthesis code is an important tool to investigate the process involved in star formation in various galaxies. The UV wavelength range is uniquely able to characterize the stellar content of young starbursts, and when combined with optical data, to show signatures of older stellar populations. It becomes a powerful diagnostic to trace the history of a galaxy and identify the various processes that may have influenced it. New data are needed to perform a global analysis addressing specific questions related to star formation in individual galaxies. For example, are the average and range of masses, ages, metallicities, star formation rate, or initial mass function of individual clusters different with respect to the galaxy properties (mass, metallicity, merger, isolated, bar)? Where do we see the most important age and metallicity gradients? How are these gradients useful to identify a sequential mode of star formation? From the prediction of the mechanical energy output from stellar winds and supernovae in the older clusters of star formation, can we reconstruct observed sequential star formations and predict as well blowouts in the whole galaxy? Can we find a preference for the sequential mode of star formation in isolated galaxy? What is the impact of a bar in feeding different region with gas? The sample of objects studied so far also lack a wide range in metallicity to study, for example, its effect on the initial mass function. Characterizing stellar formation in galaxies in clusters is a first step to investigate the importance of interactions. Furthermore, in the central region of a cooling-flow cluster, it is also predicted that the gas will cool down to a molecular state and eventually form stars. The role of an active galactic nucleus is believed to be an important factor in delaying star formation, but this needs to be confirmed with more direct observations of young stellar populations in the cluster central galaxy. At the same time, individual massive stars and their stellar winds will be studied as they provide the foundation for stellar evolutionary theories and population synthesis codes. Finally, these studies will bring new constrains for hydrodynamical modelling of galaxy formation in clusters where the massive star feedback to their environment must be considered.

2.6 - Active galactic nuclei

Active galactic nuclei (AGNs) are prominent in the Universe at all redshifts, from the most distant quasars to the nearby cores of massive elliptical galaxies such as M87. Peak energy emission in AGNs occurs in the UV. The UV continuum, apparently thermal in nature, is believed to originate from the accretion disk that is feeding the supermassive black hole. The UV continuum may also be driving many of the observations at other energies, such as the UV/optical emission lines and X-rays. Understanding the characteristics of this primary component draws a more complete picture of the AGN phenomenon.

- <u>Rapid variability</u> - The origin of rapid UV/optical variability in AGN is not understood. Two possible models are variations from within the accretion disc as material flows inward, and reprocessing of high-energy emission. The two models can be distinguished by the time-delays between different energy bands. For example, in the accretion flow scenario, variations may originate from farther out in the accretion disc and propagate inward causing the continuum at higher energies to vary with a delay. On the other hand, if the lower-energy continuum is reprocessed high-energy emission then we would expect for variations to originate in the UV. Contemporaneous observations between the UV and other wavebands will be used.

- <u>Long time scale variations</u> - X-ray observations of AGN often reveal dramatic low-flux states, which typically last for several months. Two possible explanations include absorption of the primary continuum or reflection. In the absorption scenario, the flux drop should also be manifested in the UV. Triggered UV observations of AGN in a X-ray low-flux state can reveal the mechanism responsible for the deep flux drops. If indeed absorption, UV data can constrain the location and composition of the absorber.

- <u>Connection between UV and X-ray absorption/outflows</u> - An ongoing debate is whether the apparent absorption seen in the X-ray spectra of AGN is the same as that seen in the

UV. High-quality UV spectra can tightly constrain the location and velocities of a UV absorber.

The proposed observations require low-resolution (R = 5000) spectra of a large number of objects, with repeated observations of key targets on a timescale of hours to weeks. Coordinated observations with other observatories might be required.

3 - Canadian expertise

Ever since the launch of the first space observatories, Canadian astronomers have been recognized world-wide as leaders in ultraviolet spectroscopy. Most members of the DWG have ***decades*** of experience with the analysis of ultraviolet spectroscopic data and have been involved in the design or the support of astronomical instruments and even space telescope missions. Through the leadership of the Canadian Space Agency, industrial expertise in space missions is now also widely recognized. Both academia and the industry in the country are now mature enough to lead a space-based mission.

3.1 – Academic expertise

Philip Bennett – With a background in numerical radiative transfer and stellar atmosphere modelling, Philip Bennett also has extensive experience in observations of cool stars, mostly in the ultraviolet using IUE, HST/GHRS, HST/STIS and FUSE, but also in the optical (DAO, CFHT) and the radio continuum (VLA). He has been Principal Investigator on 14 U.S. research grants from NASA and STScI. After 13 years at the University of Colorado (3 years as a JILA postdoctoral fellow working with Jeff Linsky and Alex Brown, and 10 years on the research faculty of the Center for Astrophysics and Space Astronomy), he returned to Canada in 2005. He is currently a Scientist VII with Eureka Scientific, Inc., and an Adjunct Professor at Saint Mary's University in Halifax, NS.

Alex Fullerton (Space Telescope Science Institute/Herzberg Institute of Astrophysics) was one of two Canadian support astronomers for the FUSE mission (1997 – 2007). He has substantial expertise with UV instrumentation and direct knowledge of the day-to-day operation of a satellite observatory. He was a science analysis team leader during optical end-to-end testing of the FUSE satellite at the Goddard Space Flight Center, and developed software for rapid analysis and archiving of the images that were obtained during these tests. After launch, he participated intensively in the development of the CalFUSE data processing pipeline, and lead efforts to characterize the detector flat fields as well as a variety of instrumental anomalies. On the scientific side, Fullerton is a world expert on the stellar properties of hot, massive stars.

Laurent Drissen – After a Ph.D. thesis on the massive star population of the nearby galaxy M33 (1990), Drissen spent five years at the Space Telescope Science Institute (Baltimore, MD) where he participated in the analysis of the first series of Hubble telescope data. He was granted observing time on Hubble a dozen times as principal investigator, collecting images and spectra of massive stars. Holder of the Canada Research Chair on Massive Stars and Hyperspectral Imagery, professor at the physics department of Université Laval, and author or co-author of a hundred publications, he has supervised the science planning related to the design, construction and use of two instruments (SpIOMM and Panoramix-II) for the Observatoire du mont Mégantic. He has managed about 1.5 million dollars in research grants over the past 6 years (CRC, CFI, NSERC, FQRNT), and was the Scientific authority on two CSA grants to ABB.

Carmelle Robert – Expert in the analysis of UV spectra from massive stars and starburst galaxies, Carmelle Robert spent four years at the Space Telescope Science Institute where she developed a population synthesis code used to determine the global properties of young star clusters. An active member of the Canadian UVIT team, she has managed an NSERC grant (Special Research Opportunity program; total $326 070) for the pre-launch activities of the UVIT mission. Her mandate was to coordinate the funding to the different science and technical team members to ensure the success of the science calibration and the science planning of the mission. She was also granted $20 000 from the Shastri Institute to organize the meeting of the Indo-Canadian Astrosat/UVIT team at the CSA headquarters in October 2007. She was head of the scientific and local organizing committee for this meeting.

John Hutchings - He has been involved in the design, flight planning, commissioning, data processing and operations of many space-based observatories, including IUE (Science working group) and Hubble (GHRS and STIS teams). He is the Canadian project scientist for FUSE (1981 – 2007), UVIT (1996 – present) and JWST (2003 – present).

3.2 – Industrial expertise

The DWG has identified four Canadian companies with ample experience with space missions : ABB Bomem (Québec City, QC) ; COM DEV (Cambridge and Kanata, ON); Routes AstroEngineering (Kanata, ON), and Bristol Aerospace (Winnipeg, MB).

ABB Bomem is one of the major players in optical instrumentation for space applications in Canada. They delivered in 2007 the interferometer module of the TANSO-FTS, one of the two instruments onboard JAXA's GOSAT satellite launched in January 2009 which aims at monitoring the Carbon Dioxide concentration in support to the application of the Kyoto Protocol. ABB Bomem is also supplying optical payload as part of the new generations of weather satellites in Europe, Asia and United States to be launched starting in 2010. They also delivered in early 2009 the optical ground support equipment for the Canadian contribution to the James Webb Space Telescope. ABB Bomem is actively pursuing opportunities in many other future space programs (PCW, CLARREO, SOAR, Premier, ...).

COM DEV also has a tremendous heritage with Canadian space astronomy. They were the prime contractors for the Fine Error Sensors (FES) on FUSE, which were the hardware components contributed by CSA to that program. These extremely sensitive CCD cameras provided full-field images for pattern recognition and target acquisition, and also obtained and analyzed the guide star images required to keep the telescope pointed stably during science exposures. The FES cameras proved to be robust and reliable, and kept the satellite operating even as other critical components of the attitude control system failed. COM DEV is also the prime contractor for Canadian hardware contributions to the James Webb Space Telescope.

Routes AstroEngineering provides critical expertise in the area of UV detectors, which is of extraordinary importance for future UV observatories. Routes are currently packaging the UV detectors for the UVIT satellite, which the DWG considers to be the pivotal Canadian precursor to the spectroscopic mission we are proposing here.

Bristol Aerospace (now part of Magellan aerospace corporation) has nearly 80 years of experience in space project management, launch vehicle design and testing, spacecraft conceptual design. Bristol was the spacecraft prime contractor for the SCISAT-1 ACE Mission. In this capacity, Bristol was responsible for: the development of the spacecraft bus, integration of the FTS and Maestro instruments, spacecraft environmental testing at DFL, launch vehicle integration support to Orbital Sciences Corporation (OSC) on Pegasus-XL, support for ground segment compatibility testing with CSA SatOps, development of the Realtime Spacecraft Operations and Training Simulator, support for Launch and Early Operations Phase (LEOP) and spacecraft commissioning.

Bristol was selected in 2002 by CSA to perform Phase A/B development of the Multi-Mission Small Satellite Bus (MMSSB) to address the requirements of anticipated CSA missions. Bristol has led or participated in numerous Phase 0 and Phase A small satellite mission concept studies based around the MMSSB. These include: Chinook, RADARSAT Constellation and ORBITALS.

4 - Opportunities

Ultraviolet astronomy is at a critical junction. Routine access to this region of the electromagnetic spectrum has enabled fundamental advances over the breadth of observational astrophysics since the first decade of the space age. Essentially all sub-disciplines have benefited from observations made in this waveband, which is extraordinarily rich in resonance lines. It is profoundly disturbing that there are no plans to maintain access to these key diagnostics beyond the installation of the Cosmic Origins Spectrograph (COS) and the refurbishment of the Space Telescope Imaging Telescope (STIS) on the Hubble Space Telescope (HST). The final servicing mission to HST is scheduled for 2009 May. Given its age and history of gyro and instrument failures, the remaining operational lifetime of HST is difficult to estimate. But only the most optimistic think that its UV spectroscopic capability will still be available to the astronomical community by 2019.

The closing of the UV window to high-resolution spectroscopy represents a looming disaster for quantitative astrophysical analysis by astronomers world-wide. However, this disability also represents a tremendous opportunity for the Canadian astronomical community and the Canadian Space Agency to become a true leader in space astronomy. The DWG sees two paths forward.

4.1 - A Canadian UV Spectroscopic Satellite

The DWG desires to have Canadian astrophysicists recognized as leaders in space astronomy, rather than minority partners (Odin, FUSE, JWST). Our recommendation is that the CSA encourages these aspirations by leading the conception, development, and implementation of a small- or medium-size facility that will provide the world-wide astronomical community with continued access to UV spectroscopy during the coming “Dark Age”.

In response to a call for proposal (sollicitation number 9F028-070111/A), members of the DWG teamed with industry leaders (ABB-Bomem, COM DEV and Bristol Aerospace) to propose to study innovative concepts of a small orbiting telescope equiped with a spectrograph capable of obtaining high S/N, low and high resolution (R = 1000 and 60 000) spectra in the UV regime

(110 – 320 nm) in the context of a Multi-Mission Small-Satellite Platform. The mission requirements of this mission, the Canadian Ultraviolet Spectroscopic Explorer – CUSE, are determined by the science drivers discussed in section 2, and can be summarized as follows :
(1) Spectral range : from 105 to 320 nm
(2) Spectral resolution : R = 1000 to 60 000
(3) Mirror size : 0.5 – 1.0 meter
(4) Apertures : from 1 arcsecond to 30 arcseconds diameter, with multi-object capability
(4) Orbit : low Earth orbit with low inclination to avoid the South Atlantic Anomaly.

A pivotal recognition is that due to recent leaps in the quantum efficiency of UV detectors, a modest 0.5 – 1.0 m telescope can provide substantial improvements in sensitivity over IUE or FUSE. We envisage the observatory to be a cost-effective work-horse facility with a price-tag of less than $200 Million, rather than a cutting-edge “flagship” mission (which will cost well in excess of $1 Billion, and seems well beyond Canada’s funding ability).

There are many scientific drivers for continued access to UV spectroscopy as detailed in section 2. Through robust and simplified design, we envisage simplified modes of operation that both minimize lifetime costs and promote longevity. This longevity will permit Canada to dominate the world of UV spectroscopy throughout the coming “Dark Age”, and will also enable synoptic studies of astrophysical phenomena over scientifically interesting time scales of months to years.

The DWG has already identified the requisite personnel in the community of Canadian astronomers and their industrial partners (Section 3) required to lead such an mission. The DWG also believes that leadership of a mission of this scope will nurture technological growth and the education of the next generation of scientists. The cost is steep: it will be similar to the total cost of the entire FUSE mission (USD 220 Million). But the pay-off in terms of scientific return and credibility in the space-science community will be unparalleled. Leadership through the UV “Dark Age” will take the Canadian space astronomy community to the new heights of credibility. We should also consider including other international partners in this project to reduce the cost to the CSA.

4.2 - Partnership in the Next UV-Optical Infrared (UVOIR) Observatory

Members of the DWG have been following recent developments in the United States concerning new NASA mission opportunities in the UV[1] very closely. In addition to the meetings indicated in Section 1, Fullerton is participating (at no cost to the DWG) in a NASA-funded concept study for the THEIA Observatory, which has general astrophysical capabilities (wide-field imaging and UV spectroscopy) as well as highly specialized coronagraphic capabilities for planet-finding and characterization. By actively participating in these activities, the DWG has kept fully abreast of opportunities for CSA to partner with new NASA missions.

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[1] We note in passing that no interesting opportunities were promoted during the recent ESA Cosmic Visions down-selection.

Most of these activities have been occuring in order to inform the Astro2010 decadal survey of astronomy and astrophysics in the United States, which began in 2009 January. It is much too early to say which, if any, of the various concepts will be promoted by the decadal survey; and even then the funding landscape for future NASA missions is at present rather uncertain. However, it seems likely that two potentially interesting "flagship" missions will be recommended:

- A "Dark Energy" mission, which will emphasize wide-field optical/IR imaging but may have general-purpose spectroscopic capability added in order to make the mission more appealing to a broader community as a successor to HST.
- A planet-finding mission, which might incorporate the concept of a free-flying occulter to achieve the desired levels of suppression of light from the host star. Examples of this concept that are currently being studied include THEIA and the New Worlds Explorer. Although studies of exoplanets are the primary science drivers for these facilities, the choreographed maneuvers required to position the external occulter accurately means that ~75% of all observing time is available for general astrophysics. Thus, both these concepts also incorporate general-purpose observatories that can be viewed as a successor to HST. THEIA explicitly includes wide-field imaging (via the Star-Formation Camera [SFC]) and high-resolution UV spectroscopy (via the UV Spectrograph [UVS]).
- It is also possible that a "Hubble on steroids" mission like the Star-Formation Observatory (SFO) will be recommended. This observatory has a smaller aperture, but advanced capabilities for wide-field imaging and UV spectroscopy.
- Although a conceptual study for a very large UV observatory ("ATLAST") was funded, its primary goal is to identify key enabling technological developments. It is unrealistic to suppose that a mission to launch an 8 or 16m UV telescope will be feasible during the next decade.

All these concepts translate to expensive "medium-class" (USD 600 Million cap) or large "flagship" missions (more than USD 1 Billion). Indeed, the life-cycle costs for THEIA are more like USD 5–6 Billion, which is similar to other major observatories like HST and JWST. The feasibility of some of the flagship concepts depends to some extent on the availability of the Ares EELV, which is still in development.

Given the expense of these missions, it is not unreasonable to expect that they represent excellent opportunities for CSA to play its traditional role as a minority partner for a NASA mission. Even a small partnership will be expensive, but experience suggests that the costs are highly leveraged, particularly in terms of scientific yield. Canadian industry also benefits.

However, it is premature to assess the viability of these missions until after the work of the Astro2010 decadal survey is complete. The report will not be released until the summer of 2010. Even without knowing what the recommendations will be, it is clear that (a) all these missions would take at least 10 and probably 20 years of development to come to fruition; and (b) cannot be started for financial reasons until after the launch of JWST (currently baselined for 2013). Thus, even if one of them should go forward, a large new mission will not prevent the looming Dark Age of UV Astronomy.

4.3 – Partnership in the World Space Observatory (WSO-UV)

Another project of interest to the DWG is the World Space Observatory – UV (http://wso.inasan.ru/index.html), an international concept led by Russia with major contributions from Spain, Germany, China and Ukraine. In 2007, the WSO-UV appeared as a potentially very interesting project : a 2m-class telescope dedicated to ultraviolet astronomy and well-equiped with high quality spectrographs (détails can be found in the web page above and in Shustov et al. 2009, Astr. & Space Science 320, 187; Kappelmann et al. 2009, Astr. & Space Science 320, 191). Drissen has indeed contacted the PI of the mission, Dr. Boris Shustov (Institute of Astronomy, Russian Academy of Science), as well as the German PI, Dr. Klaus Werner, responsible for the the high resolution spectrograph, in early June 2007 (copies of these emails can be obtained upon request). Both were enthusiastic about a possible Canadian participation. Dr. Shustov even suggested a few potential Canadian contributions, such as : ground-based radio links, optics coatings, or fine guidance sensors. The DWG did not engage further in this path as its members felt that the most technically and scientifically rewarding aspects of the WSO-UV had already been assigned to other partners and rather pursued the Canadian-led project depicted in section 4.1. The funding and readiness status of the WSO-UV in 2009 are not clear at the moment. Possible collaborations with the WSO-UV team members, in the context of a Canadian-led observatory, should be considered.

5 - Recommendations and conclusions

Either of these paths – developing an all-Canadian mission for UV spectroscopy or becoming minority partners in an ambitious, multi-purpose NASA or Russian mission – represents an opportunity for growth, both for the Canadian astronomical community and the Canadian Space Agency. Particularly because it will allow Canada to assume a leadership role in space astronomy during the looming gap in UV capability (between ~2015 and ~2025 at least), the DWG recommends that an all-Canadian mission be pursued vigorously. If we are going to go with the recommended all-Canadian mission, we stress that we need to proceed quickly. We can do this because the mission is not trying to do the really hard observations that the big U.S. flagship missions are trying to so. The all-Canadian proposal is for a robust, reliable UV telescope that uses technology available now (or soon, in the case of the UV CCD detectors). Even so, it will still be 5-7 years to launch if we start tomorrow. Longer delays will only prolong the UV Dark Ages, and render the all-Canadian mission less attractive. In our absence, some other mission will eventually come along to fill the gap, and the window of opportunity will close.

If instead we chose to become a minority partner in a large international mission, the DWG recommends that the Canadian contribution be of substantial technical and scientific content.

Either approach will reward Canadian astronomers with a rich harvest of scientific data.

Appendix A – Membership

A.1 - Original Membership :

Co-Chairs :

Laurent Drissen, Université Laval – Massive stars and instrumentation

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Phil Bennett, Saint-Mary's University – Cool stars

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Alex Fullerton, Space Telescope Science Institute – Hot stars, JWST instrument scientist

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Carmelle Robert, Université Laval – Starburst galaxies

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(418) 656 2131 ext-3612

Anthony Moffat, Université de Montréal – Massive stars, wind collisions.

moffat@astro.umontreal.ca

(514) 343 6682

A.2 - New members :

One of the first tasks of the DWG was to enlarge its membership, in order to reflect better both Canadian scientific interests in the UV region of the spectrum and the geographical diversity of the Canadian astronomical community.

The following people thus joined the DWG during 2007 :

John Hutchings	National Research Council/Herzberg Institute of Astrophysics
Neil Rowlands	COM DEV
Patrick Hall	York University
Nicole St-Louis	Université de Montréal
Luigi Gallo	St-Mary's University

A.3 – Industrial partners :

The working group then welcomed the input from the following industrial partners for discussions and work on the CUSE proposal : ABB Bomem (Québec City), COM DEV (Ottawa) and Bristol Aerospace (Winnipeg). While most of them were not members of the DWG, the following worked in close cooperation with its members:

ABB Bomem: Frédéric Grandmont (technical lead, project engineer), Sylvio Plante (electronics engineer), Daniel Gingras (mechanical engineer), Jean-Pierre Bonneville (program manager).

Bristol: Paul Harrison (controls system engineer),Victor Wehrle (mission analyst), Jean-François Thibault (mechanical designer), Shawn Beaudette (system engineer), Michael Labib (project lead).

COM DEV: Neil Rowlands (member of the DWG)