THE JANUARY 26, 2001 FIREBALL AND IMPLICATIONS FOR METEOR VIDEO CAMERA NETWORKS

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Abstract. A bright fireball was observed from central and southern Alberta in the early evening of January 25, 2001 (January 26 UT). The event was recorded with three all-sky video cameras in and near Edmonton, on one video camera located in Calgary, and by many visual observers. Visual and taped observations indicate an agreement of a duration of 2 to 4 1/2 seconds. There were several reports of sonic booms. The peak brightness was comparable to the Full Moon. Analysis of all available data indicates that a meteorite fell near Big Valley, Alberta, although several field searches failed to recover any fragments. Improvements to equipment and methods of analysis will improve the chance of recovering meteorites in future using all-sky cameras and refined astrometric measurement techniques.

Résumé. Un bolide brilliant a été observé le soir du 25 janvier 2001 (26 janvier, temps universel) du centre et du sud de l'Alberta. L'événement a été enregistré par trois appareils vidéo captant tout le ciel visible des environs d'Edmonton, par un appareil à Calgary, ainsi que par maints observateurs visuels. Ces observations ont indiqué que l'événement a duré de 2 à 4,5 secondes. Des éclats soniques ont été entendu et l'intensité lumineuse se rapprochait de celle de la pleine lune. Une analyse de toutes les données recueuillies indique qu'un météorite est tombé près de Big Valley, Alberta, quoique des recherches dans les champs environnants n'ont réussi à récupérer aucun fragment. Des améliorations de l'équipement et des méthodes d'analyse devront à l'avenir améliorer la probabilité de récupérer des météorites, en se servant de caméras 'tout ciel' et de techniques de mesure de données astrométriques.

1. Introduction

The value of meteorites as sources of information about the formation and early evolution of the Solar System is well recognized (Wasson 1985). The value of a meteorite is greatly enhanced if its solar orbit is known and, hence, if its original dynamical relationship with other Solar System objects can be established.

Several meteor camera networks have been operated in Canada, Europe, and the United States (Halliday *et al.* 1978). Observation of a meteor event from two or more sites, along with angular velocity information, permits determination of a fall zone for any surviving fragments. This information also allows determination of the trajectory in space prior to entering Earth's atmosphere, and with appropriate corrections, the original orbit. In addition, it has been possible to estimate the initial mass and derive limited information about the physical and mineralogical characteristics of some meteoroids from camera records using either the integrated brightness of the event or the observed deceleration (Halliday *et al.* 1989).

The Canadian Meteorite Observation and Recovery Project (MORP) was in operation in the Prairie provinces from 1971 until 1982. The Innisfree (Alberta) meteorite was recovered as a direct result of MORP observations (Halliday *et al.* 1978). The MORP cameras were optically very sophisticated, used film to record observations, and were expensive to build and to operate. One of the authors (RS) has developed an all-sky camera using inexpensive, off-the-shelf components. One such camera is illustrated in Figure 1. Arrays of four (usually) such cameras have been installed at several locations in North America. The Northern Alberta array in early 2001 consisted of a camera mounted on the roof of the Physics Building on the campus of the University of Alberta (hereafter UA); a camera at King's College Observatory, 18 km east of Edmonton (hereafter BM); another located at Alister Ling's home in southwestern Edmonton (hereafter AL); and a fourth camera on the campus of Athabasca University, approximately 130 km north of Edmonton (hereafter AU). The geographic coordinates of the four cameras are listed in Table 1.

Table 1.
Northern Alberta All-Sky Camera Array

Camera 1-UA	University of Alberta (113° 30.4´ W 53° 31.5´ N)
Camera 2-BM	Martin Acreage (113´ 10.1´ W 53° 30.8´ N)
Camera 3-AL	Ling Home (113° 34´ W 53° 28.5´ N)
Camera 4-AU	Athabasca University (113° 18.4´ W 54° 42.9´ N)

Each camera consists of a Konica Camera Model FC-08B, supported on a tetrapod approximately one metre above a 46-cm diameter convex mirror of the type commonly mounted in the ceiling above intersecting corridors in hospitals. The signal is sent to an array of three VHS video recorders, each of which operates for 8 hours in sequence, to provide 24-hour coverage of the entire sky. A simple heating cable mounted inside the hemispherical mirror prevents condensation and a build-up of snow except under very extreme conditions. The cameras have operated through three winters, and have proven to be very robust; some minor problems have arisen due to low temperatures, extremes of humidity, and tape and video recorder wear.

The monochrome cameras used have a nominal minimum illumination of 0.08 lux at f/1.2 and a 1/3 inch CCD with 771 by 492 approximately 7 micron pixels. A Computar TG0812FCS-3 lens, with 8mm focal length and auto-iris control from f/1.2 to f/360, is pointed down at the dome mirror, which is effectively hemispherical with radius 23 cm. This combination results in a limiting apparent stellar magnitude of about −2 from a dark, rural site, and of approximately −3 from within Edmonton city limits. As a result, stars are not detected on individual frames. The two brightest planets, Venus and Jupiter, have been recorded routinely. The stated magnitude limit easily recorded the fireball events of interest, since those that drop meteorites are usually brighter than −10 magnitude. There is, however, a limitation in calibrating the images, that is, in converting a pixel coordinate on an image to a position (azimuth and altitude, or Right Ascension and Declination) on the sky. It is possible to detect stars by stacking successive frames from the videotapes and this provides known points for direction calibration. For this we have also used the Iridium satellite system. The Iridium satellites produce "flares" when, for brief intervals, they are so positioned relative to Sun and a ground-based observer that a reflection of sunlight is directed toward the observer. Iridium flares are predictable: we have used data provided at `www.heavens-above.com`. Even with allowance for events lost due to inclement weather, there had been sufficient numbers of Iridium flares well distributed over the sky to permit calibration of the system and determination of the location of events in the sky to an accuracy of 0.5 to 1 degree. Despite our calibration prior to the event using these methods, we recalibrated, for this event, using stacked sky images that showed bright winter stars near the path of the fireball. This would not have been possible had the fireball been seen in a different direction.

Figure 1. – Sandia meteor camera on the roof of Athabasca University. A video camera is housed in the vertical white tube and aimed downward at the convex mirror. Power and video cables run to recorders inside the building.

During approximately 12 months of operation preceding the January 25 fireball, the Edmonton array recorded several bright meteors. Numerous fireballs were subsequently recorded during the November 2001 Leonid meteor storm. The January 25 fireball was the only one recorded until the end of 2001 with characteristics of surviving meteoritic material that might easily found on the ground.

2. Observational Data

On the night of Thursday, January 25, 2001, at 19:21 MST (02:21, January 26, UT), several undergraduate student volunteers at the

Figure 2. – Stacked image of fireball as seen from the University of Alberta. This composite of about 120 frames shows the fireball trajectory much as it would have been perceived by the eye. In contrast, each frame shows the fireball "frozen" at each point along the path. The apparent width of the fireball trail is due primarily to blooming in the camera. The lack of sky objects to use for calibration is apparent: only Venus (near bottom) and Jupiter (left of fireball) are apparent in this image despite stacking. East is at the top and south is at the right.

Campus Observatory of the University of Alberta in Edmonton visually observed a fireball falling toward the southern horizon with a duration of a few seconds. Figure 2 gives an idea of the visual appearance of the fireball and some idea of the appearance of the taped output from one of the all-sky video cameras. A check of the all-sky camera tapes at the nearby UA camera confirmed the event. Shortly thereafter, members of the public began to phone the universities and science centres in Calgary and in Edmonton. Over the following month or so, we sent requests to radio stations and to newspapers requesting additional reports. Good sky conditions and a suitable time of day resulted in a large number of people over a wide geographic area seeing the event.

The event was recorded with the two all-sky cameras within Edmonton (UA and AL) and with the one a short distance east of Edmonton (BM). The AU camera experienced a tape failure several minutes before the event. Several months earlier, one of us (Hladiuk) had begun to monitor a small portion of the sky with an ordinary video camera pointed through a window of his home located in Calgary. Fortunately, the camera was pointed toward the north and this event was recorded. All visual observers in the Edmonton area agreed in placing the event low toward the south and moving right-to-left (*i.e.* west to east), while all observers in the vicinity of Calgary placed it low in their northern sky moving left-to-right (*i.e.* again, west to east). Observers in central Alberta (*e.g.* Red Deer, Ponoka) observed it high in the sky, in some instances close to the zenith, and moving toward the southeast.

Many observers reported a terminal burst, and this was also apparent in all the video records. Only a few individuals, located near Stettler, claimed to have heard a "sonic boom" (Hildebrand 2001). Most observers reported a visible duration of 2 to 4 seconds, which was confirmed on the videotapes. At its peak, the fireball was said by eyewitnesses to have been as bright as the Full Moon.

From the initial analysis of the observations it appeared that the fireball had traveled from NW to SE, passed close to the zenith near Red Deer (113° 48´ W, 52° 16´ N), had a terminal burst SE of Red Deer, and a projected fall zone north, or northeast, of the town of Big Valley (112° 46´ W, 52° 2´ N). Several individuals reported fragments continuing very briefly after the terminal burst. A subsequent frame-by-frame analysis of the tapes confirmed the survival of material after the principal burst.

The duration as determined from the tape records was 3.83 s (UA), 4.27 s (AL), 2.27 s (BM) and 3.13 s (DH). The BM record was shorter than the others due to frost on the mirror.

3. Camera Calibration

Iridium satellite "flares" and stars on co-added (stacked) frames provide the principal means for calibrating positions. At times, stellar objects as dim as apparent magnitude +2 are detectable through image stacking, which builds up brightness where they are located while averaging out noise. The apparent motion of the stars due to rotation of the Earth limits how much stacking can be done. Once a star's "motion" shows up on the image, all advantage of stacking is lost. Since the stars in the southern sky were needed for the Edmonton area calibrations, in practice about 1000 images could be stacked and only the brightest winter stars emerged in the images. For a particular event, the limitations to accuracy in determining the trajectory of the fireball are the lack of reference objects near the path and strong field curvature, especially close to the horizon. Luckily, this fireball passed near the bright southern winter stars, minimizing the first problem. To counteract the second problem, a quadratic relation between radial location of pixels and altitude above the horizon was used.

To further increase accuracy, for calibrating azimuths from the three cameras in or near Edmonton, we used artificial lights near the horizon. Their azimuths were determined via GPS relative measurements, aerial photo measurements, and surveyed measurements from the camera sites.

To calibrate DH's video camera in Calgary, a 35-mm camera was used to take calibration photographs from the same location. The 35-mm camera frames were digitally overlaid on video frames, with reference to ground-horizon features and to measuring staffs, to extract the required astrometric information.

4. Trajectory Solution

To solve for the atmospheric path of the fireball the technique of Borovicka (1994) was employed. This algorithm uses an initial "best-guess" atmospheric path as a starting point for a least-squares solution to sightlines from all stations. The program iterates the path until a minimum is reached in the deviations of the sightlines summed over all stations. Calibrated frames spaced approximately evenly across each of the video records from stations AL, DH, BM, and UA had fireball positional measurements made and employed for a first solution. Due to frosting of the mirror, the absolute BM astrometry was noticeably poorer than at other stations; its positional information was dropped from the final solution. We do not expect this to significantly affect the final results, as the positional information from AL, BM, and UA are very similar, due to the closeness of these stations. Thus our solution uses AL, DH, and UA results to define the atmospheric path. The program was executed for slight variations of input parameters and found to give a stable solution. Table 2 summarizes the result. The earliest point is defined by the start at AL as near as 90 km, somewhat above typical start heights for fireballs in this size range, but not unrealistic (Ceplecha & McCrosky 1976). The burst and endpoint both occurred at very typical altitudes for such a modest fireball. We expect, that had photographic methods been used with greater sensitivity than our video equipment, the end height might have been determined as several kilometres lower than what we determined.

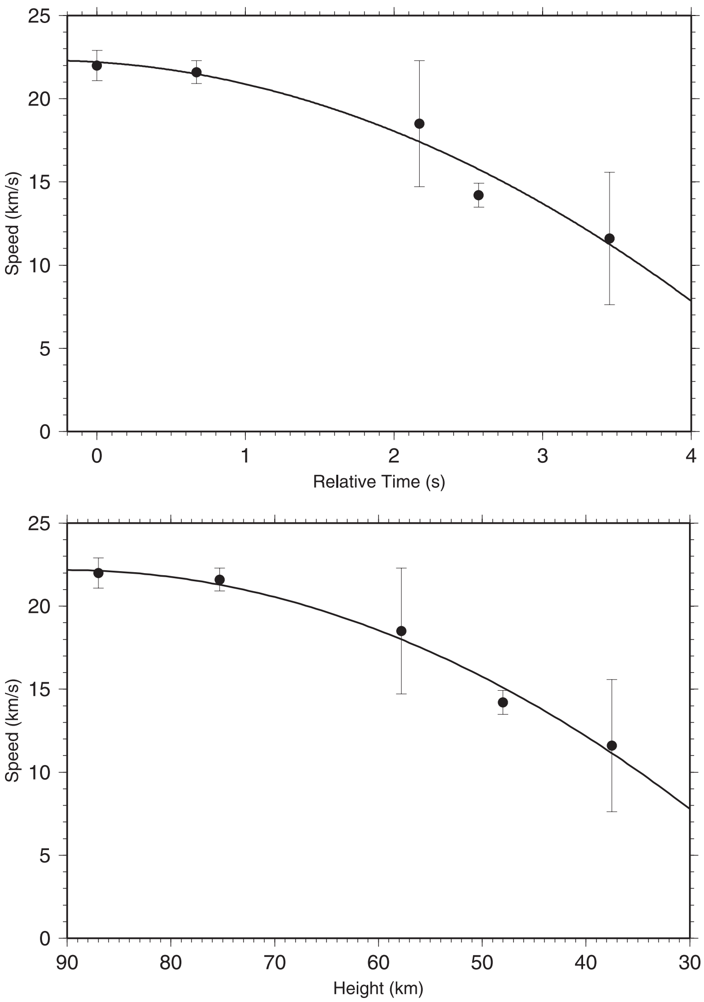

Figure 3. – Velocity as a function of time (top) and of height (bottom) for the January 26, 2001 fireball. Error bars reflect the uncertainty in measured positions as defined by the deviations of the sight lines (in km) from the best-fit trajectory.

5. Detailed Velocity Analysis

The camera in Calgary (DH) achieved the best spatial resolution, since it was recording directly through its lens and not having its scale reduced by use of a convex mirror. With a preliminary determination of the trajectory obtained by combining all reliable camera and visual observations, an approximate entry velocity of ~22 km s^{-1} was found from a frame-by-frame analysis of the DH tape. Repeating the analysis with the AL tape also resulted in an entry velocity of ~22 km s^{-1}. However, the precise velocity profile is relatively poorly determined due to the low astrometric accuracies of individually measured images relative to the high temporal resolution (30 frames per second). As a result, the best velocity profile was found by using only those sets of points from AL and DH that had the smallest line-of-sight deviations from the fireball path. The fits shown are quadratic and for velocity vs. time the curve has the form:

Table 2.
Computed Fireball Trajectory

Begin Point	87.0 ± 0.7 km	113.392 ± 0.007°	52.730 ± 0.009°
Burst Point	37.8 ± 1.5 km	112.870 ± 0.12°	52.407 ± 0.060°
End Point	35.8 ± 0.6 km	112.747 ± 0.005°	52.400 ± 0.007°
Radiant altitude	39.2 ± 1.1°		
Radiant azimuth	135.1 ± 1.2°		

$$\boldsymbol{v} = \left(22.2 \pm 1\right) - \left(0.563 \pm 1\right)\boldsymbol{t} - \left(0.720 \pm 0.4\right)\boldsymbol{t}^2 \ .$$

For unknown reasons, the velocities obtained from the UA tape show a large scatter, especially in the early sections of the trajectory. The varying error bars reflect in part distances from the cameras and in part uncertainties in measuring the true position due to blooming, and we consider the velocity profiles to be fairly crude. Nevertheless, some quantitative information about the fireball can be obtained from them.

Our formal analytic fit suggests a velocity of 22.2 ± 1 km s^{-1} at 90 km altitude. We expect some additional deceleration before this point, but cannot quantify the magnitude without knowledge of the mass of the body. However, as estimated below, with a mass between a few tens to (more likely) hundreds of kg, the correction to V_∞ amounts to <0.1 km s^{-1}, which is much smaller than our formal error margin (Spurny 1997). An estimate of the mass for the fireball can be made either by integrating the total light produced from the fireball (photometric mass) or by examining the deceleration of the fireball with some precision (Halliday *et al.* 1978). As we do not have an absolute photometric calibration, application of the first method is not possible. Our velocity errors are such that only near the end of the fireball path does the value of the deceleration become large compared to its error. From this measured deceleration, we may estimate the dynamic mass (m_d) as:

$$m_d = \frac{\Gamma A \delta \rho v^2}{\left(dv/dt\right)^2}$$

where Γ is the drag coefficient (~0.9), A is the shape factor (which for a sphere has a value near 1.2), δ is the meteoroid bulk density, and ρ is the atmospheric density (Ceplecha *et al.* 1998). In practice, this is the mass of the largest fragment surviving at the end of the path (terminal mass). Applying this to the deceleration at the endpoint we get a terminal dynamic mass near 1.4 ± 0.5 kg, suggesting that some material should have reached the ground.

6. Orbit

Computation of the meteoroid's nominal orbit is from the estimated initial velocity and our trajectory solution. The orbital results are shown in Table 3. This is a relatively typical Apollo-type orbit, though with a larger than average aphelion distance and a slightly large inclination. However, the associated errors are quite large, so the

Table 3. Orbit of the January 26, 2001 Meteoroid	
V_∞ (km s−1)	22.2 ± 1.1
V_h (km s−1)	39.5 ± 0.9
α_R (J2000.0)	313.0 ± 1.9
δ_R(J2000.0)	56.8 ± 1.4
α_G (J2000.0)	307.9 ± 1.9
δ_G (J2000.0)	53.5 ± 1.5
a (Semi-Major axis; AU)	3.69 ± 1.14
e (eccentricity)	0.74 ± 0.08
q (perihelion distance; AU)	0.957 ± 0.005
i (inclination; degrees)	27.3 ± 1.7
ω (argument of perihelion; degrees)	159.1 ± 1.9
Ω (Longitude of Ascending node; J2000)	306.188 ± 0.001
Q (Aphelion distance; AU)	6.4 ± 2.2
θ (True anomaly; degrees)	20.9 ± 1.9
Time since perihelion (days)	15 ± 2

aphelion may well be inside Jupiter's orbit, as is the case for most meteorite-producing fireballs (Wetherill & Revelle 1981). Comparison of this orbit with known orbits of near-earth asteroids, comets, and meteoroids reveals no close associations despite there being several thousand meteoroid orbits resulting largely from MORP. Comparisons were done using the D criterion (Ceplecha *et al.* 1998) where a value over 0.1 would have indicated a significant similarity to a given orbit.

7. Field Searches

The brightness, terminal burst, and phenomena reported by witnesses suggested early on that meteoritic material had fallen (the orbit and mass, determined later, support this). The predicted fall zone was near the village of Big Valley, approximately 75 km east-southeast of the city of Red Deer. Three field searches were conducted in April 2001, after the winter's accumulation of snow had melted, and before significant new vegetative growth. The area is typical of western prairie agricultural lands consisting largely of open and hilly fields used for grazing cattle and for the growing of crops. Stubble from the previous year's crops plus a scattering of small stones covers the open ground. A significant fraction of the stones are smooth, dark clay stones of the type commonly misidentified by the public as being meteorites. There are scattered small swamps, small stands of trees, and a few oil wells and associated hardware.

A total area of approximately two km^2 was searched by systematic sweeps, but no meteoritic material was found. Local residents, many of whom had observed the fireball, were alerted to the possibility of meteorites being found, but no finds were reported during, or following, our search.

8. Lessons Learned and Developments for the Future

One should not underestimate the time required to assemble and calibrate equipment, and the difficulty in identifying suitable locations and local operators. We knew in advance that the spacing of the Edmonton-area cameras was not good. For the purpose of determining a reliable trajectory and fall zone, the cameras should be spaced 50 to 100 km apart. In 2001, the three Edmonton-area cameras lay along a roughly east-west line of length 20 km, or so. The Athabasca University camera is well separated (north-south) from the others, but was not fully operational on the night of interest and would, for this event, have served only to confirm the azimuth obtained from the others.

The positions of cameras in their present form necessitate on-site management (*e.g.* for the purpose of changing video tapes daily). Automatic, non-mechanical operation is preferred. To that end, others and we are developing software for event detection through flash monitoring. That is, successive images are automatically compared and changes above a certain threshold from one to the next trigger the storage of a sequence of images for later analysis. With digitization directly from video, storage on a hard drive, and linking of local computers to a central site, one person could operate an array of cameras. Local events such as airplane flyovers could be distinguished from fireballs through inter-comparisons of records from two or more suitably sited cameras.

Substantial effort was put into calibrating the images, but a more refined calibration is desirable. Much of the work to calibrate the cameras took place after the event. It is important to mount the camera rigidly in what will be its permanent location, and to calibrate frequently using planets, stars, and Iridium flares widely distributed over the sky. Calibration of altitude close to the horizon is particularly difficult, but very important since most fireball events are likely to be distant from the camera and, hence, close to the horizon. Even with good calibration, the angular resolution of the cameras will not be better than 0.5 to 1 degree. Any lower resolution would preclude determination of reliable velocities.

As noted previously, the original video cameras are too insensitive to record any but the brightest planets, and the brightest stars can only be seen by stacking images. Newer, often less-costly low-light video cameras are becoming available, as are low-cost wide-angle lenses suited to meteor detection (Horne 2003). Cameras should be replaced as newer, technically superior devices become available.

Eyewitness reports are open to interpretation when they refer to local everyday events such as road accidents, but even more so when they refer to a sudden once-in-a-lifetime event such as a brilliant fireball. Eyewitness accounts have greatest value when obtained under the track or near the endpoint. The details presented by eyewitnesses can change with time, so the earlier one collects such reports the more accurate they will likely be. Objective instrumental records are much preferred, and should, in general, carry the greatest weight.

9. Conclusions

The mass of the meteoroid at atmospheric entry is estimated to have been tens to hundreds of kilograms. There would have likely been around a kilogram of surviving meteorites, but none were found in field searches in the likeliest location.

The orbital determination places the meteoroid in a typical Apollo orbit with, however, a higher-than-normal inclination.

With improved calibrations, better camera mounts, a wider distribution of the cameras in north-central Alberta, and the installation of a camera network in southern Alberta, we anticipate greater success in analyzing future fireball events, and improved prospects for the recovery of meteorites. We are *waiting* patiently for Nature to produce that next event.

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Donald Hladiuk, an active amateur astronomer in the Calgary Centre, runs his own video monitoring system that contributed to this article. His employment as a geologist at Conoco Canada has an astronomical connection through the Steen River impact structure, a trap for oil and gas.

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CANADIAN THESIS ABSTRACTS

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A Wide-Field Imaging Survey of Low-Redshift Galaxy Clusters By Wayne A. Barkhouse (wbark@head-cfa.harvard.edu), University of Toronto, Ph.D.

This thesis presents the results from a comprehensive study of 26 low-redshift galaxy clusters in order to study the radial dependence of various cluster properties. The observations were acquired using the 8k mosaic camera on the 0.9-m KPNO telescope. This dataset was supplemented by 43 clusters from the survey of López-Cruz (1997), and an additional 2 clusters from Brown (1997). Thus, a total sample of 71 clusters covering a redshift range from ~0.01 to 0.20 was available for analysis. The dynamical radius of each cluster (r_{200}) was estimated from the photometric measurement of cluster richness (B_{gc}). The cluster galaxy colour-magnitude relation (CMR) was used as a tool to minimize the inclusion of contaminating background galaxies by selecting galaxies relative to this relation. The luminosity function (LF) of individual and composite galaxy samples were constructed via the statistical subtraction of background galaxies. A robust method of comparing LFs for a variety of galaxy samples over a range of cluster-centric radius was presented. The general shape of the LFs were found to correlate with radius in the sense that the faint-end slope was generally steeper in the cluster outskirts. Colour selection of galaxies into a red sequence and blue population indicates that the blue galaxies become fainter toward the cluster central region. This result supports the scenario that infalling field galaxies have their star formation truncated by some dynamical process. The construction of a non-parametric dwarf-to-giant ratio (DGR) and the blue-to-red galaxy ratio (BRR), allowed the investigation into the change in these parameters with various cluster properties. The radial dependence of the DGR and BRR suggests that blue dwarf galaxies are tidally disrupted in the inner cluster environment or fade and turn red. The red, mainly nucleated, dwarf galaxies remain relatively unchanged with respect to cluster-centric radius, while giant blue galaxies have transformed into their red galaxy counterparts. These results provide support for the model proposed by López-Cruz *et al.* (1997) to explain the formation of cD and Brightest Cluster Galaxy halos in which dwarf galaxies get tidally disrupted in the inner cluster region.

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W4 Revisited: A Chimney Candidate in the Milky Way Galaxy Explored Using Radio Continuum and Polarization Observations By Jennifer Lorraine West (westjl@cc.Umanitoba.CA), University of Manitoba, MSc.

Compelling evidence for the existence of a fragmented superbubble above W4 that may be in the process of evolving into a chimney has been found. High latitude extension fields above the W3/W4/W5 star forming region have been processed at both 1420 and 408 MHz (21 and 74 cm) Stokes I total power as well as Stokes Q and U polarization. These observations reveal an egg-shaped structure with morphological correlations between our data and the Hα data of Dennison, Topasna & Simonetti (1997, ApJ 474 L31), as well as evidence of breaks in the continuous structure. Assuming an estimated distance of 2.3 kpc, the egg structure measures ~165 pc wide and extends ~240 pc above the mid-plane of the Galaxy. In addition the polarized intensity images show depolarization extending from W4 up the walls of the superbubble providing strong evidence that the observed continuum and Hα emissions are at the same distance as the W4 region.

A temperature-spectral-index map indicates that there are no high-energy losses in the region via synchrotron emission. This implies that energetic cosmic rays retain sufficient energy to escape into the Galactic halo. In addition the rotation measure in the region has been calculated allowing an estimate of the line of sight magnetic field ($B_{//}$) in the region to be determined. We find $B_{//} = 9 \pm 8\ \mu G$ assuming a wall thickness of 20 pc or $B_{//} = 13 \pm 11\ \mu G$ assuming a wall thickness of 10 pc and directed *towards* the observer.

In addition, some interesting features appearing in the polarization and 408 MHz datasets are examined. These features are not likely related to the W4 superbubble.

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