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ULTRAVIOLET STELLAR SPECTROPHOTOMETRY FROM A BALLOON PLATFORM

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ABSTRACT

A 40 centimeter diameter aperture, balloon-borne telescope and ultraviolet spectrometer is described and selected scientific results are briefly reviewed. The general configuration of the 0.4 angstrom resolution instrument is shown and the utilization of servo-controlled secondary mirror, image dissector detector, and special mirror coatings are discussed. An outlook for astronomical research in the mid-ultraviolet from balloon-borne telescopes is presented together with future development plans for JSC's balloon-borne payload.

I. INTRODUCTION

We wish to outline the scientific program and the existing payload configuration of JSC's Balloon-Borne Ultraviolet Stellar Spectrometer (BUSS) project and outline the plans for the future development of this ultraviolet stellar spectrometer.

The electromagnetic radiation from outside the earth is cut off shortward of about 2000 A due to the atmospheric absorption. However, if a telescope is taken above the bulk of the ozone layer, it becomes possible to extend astronomical observations to about 2000 A. From an altitude of 40 km, which is relatively easy to attain today, the entire mid-ultraviolet region becomes accessible; there exists, however, a region of higher absorption near about 2500 A (Navach, Lahmann and Huguenin, 1973). The extent of the atmospheric attenuation at a given altitude will depend on the time of the flight and the geographic area.

Because of the residual absorption present even at an altitude of 40 km, there exist some difficulties in performing absolute photometry. However, for some types of relative photometry and spectrophotometry, balloon-borne telescopes open up great opportunities. A payload weighing over 500 kg may be taken to this altitude with a balloon of about half a million cubic meters. For those types of observations that can be carried out effectively from the balloon, it provides a basically more economical way (relative to the rocket) to conduct space observations. Compared with the typical few minutes of observing time available for rockets, balloons provide several hours of observing time. Further, it provides an opportunity to utilize the newly developed techniques with the minimum lead time. In contrast, the instrumental design for an orbital experiment must usually be finalized several years prior to launch.

II. ULTRAVIOLET ASTRONOMY FROM THE BALLOON-BORNE PAYLOAD

The types of astronomical observations suitable for a balloon-borne payload in the mid-ultraviolet region (2000-3000 A) include; (a) relative photometry or spectrophotometry; (b) polarimetry, e.g., project Polariscope by T. Gohrels; (c) imagery, e.g. Project Stratoscope by M. Schwarzschild. In this article we shall discuss spectrophotometry.

The mid-ultraviolet is rich with spectral lines of once- or twice-ionized (and some more highly ionized) metals and provides astrophysical information of much interest. Investigations may be grouped into two basic areas; (1) stellar atmospheres and (2) interstellar media. The study of stellar atmospheres encompasses photospheric lines and "chromospheric" lines, although both types of studies inevitably will overlap with each other.

An investigation of photospheric lines in the mid-ultraviolet is a very useful tool in understanding the atmospheres of intermediate temperature stars (late B to F types) whose surface temperatures are such that many metals are once- or twice-ionized and their strong lines are observable in the mid-ultraviolet. It should prove an especially powerful tool in understanding the physics of the stars with anomalous abundances, such as Ap and Am stars.

The mid-ultraviolet "chromospheric" lines arising from resonance transitions of ionized metals, allowing the word "chromosphere" to include extended atmospheres, will provide exciting opportunities for furthering our comprehension of the outermost layers of stars. Such investigations should also yield valuable information on the mass flow from supergiants of early to intermediate spectral types.

Strong mid-ultraviolet resonance lines, such as the Mg II doublet at 2795 A and 2802 A and the Mg I at 2851 A, provide a vehicle to study the interstellar abundance of these elements in terms of their column density. If, for instance, the interstellar Mg II and Mg I lines are studied together, we can also investigate the electron density and temperature in the interstellar space (e.g. Boksenberg et al., 1972).

III. STUDY OF THE Mg II DOUBLET AT 2795 and 2802 A FROM THE BALLOON-BORNE ULTRAVIOLET STELLAR SPECTROMETER (BUSS)

The emission of the Ca II doublet component at 3933.7 A, otherwise known as the Fraunhoffer K line, has been employed as a useful tool for studying the stellar chromospheres, e.g., Wilson (1966). However, this emission becomes nearly impossible to detect for stars earlier in spectral type than mid-F. This has been interpreted variously as a result of the disappearance of chromospheres for stars earlier than mid-F or the observational effect due to coupling of the weakening of the Ca II K line and the rising continuum level for the stars in this spectral range.

The Mg II resonance doublet at 2795.5 and 2802.7 A ($3s^2S$-$3p^2P^o$) is the ultraviolet magnesium equivalent of the Ca II resonance doublet at 3933.7 and 3968.5 A ($4s^2S$-$4p^2P^o$). However, there are reasons to expect the Mg II doublet emission to be more prominent than that of the Ca II doublet, at least for the stars of early spectraltypes. The cosmic abundance of magnesium is greater than that of calcium; according to Allen (1963) magnesium

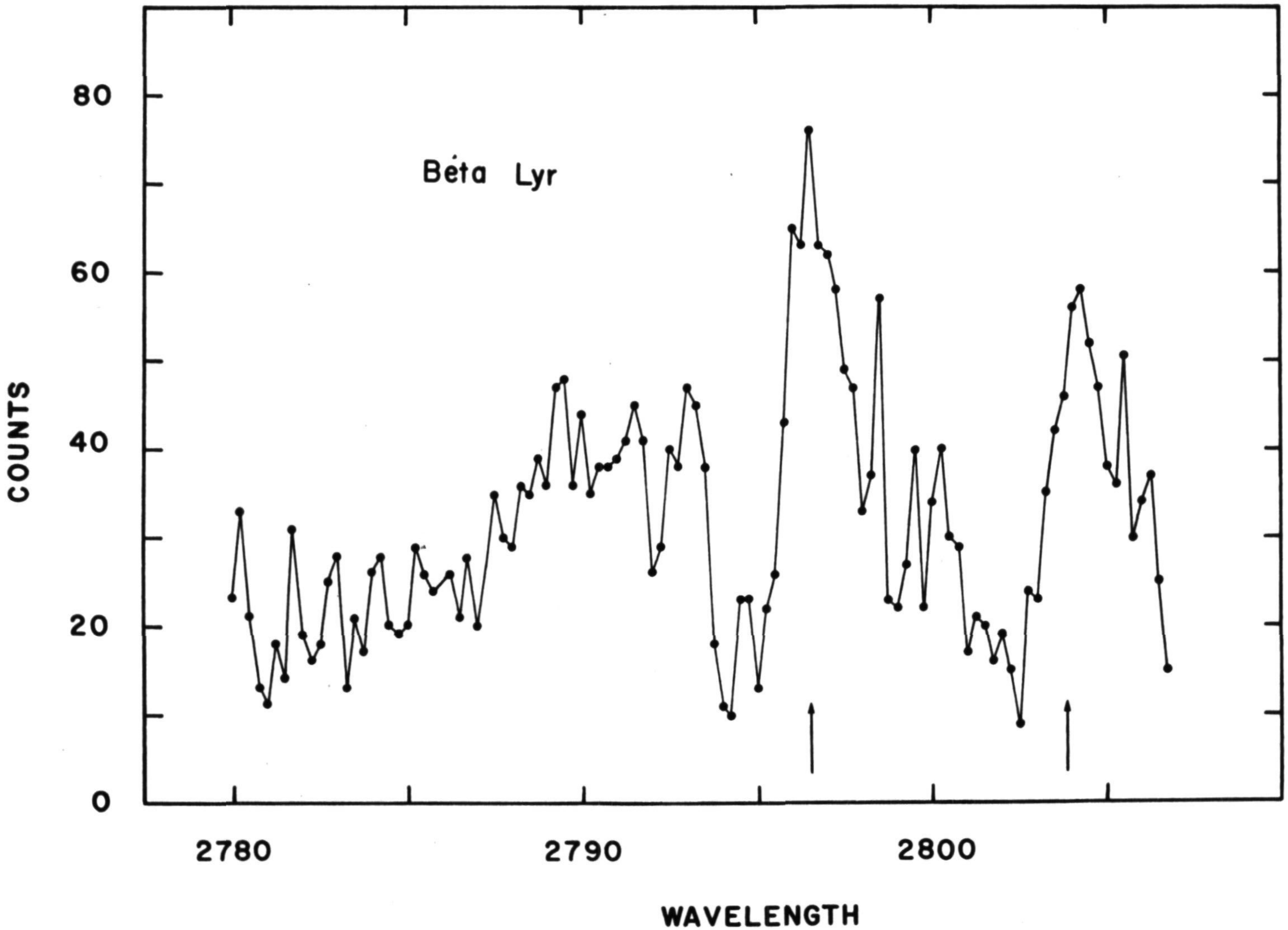

Figure 1. β Lyr Mg II Doublet Emission

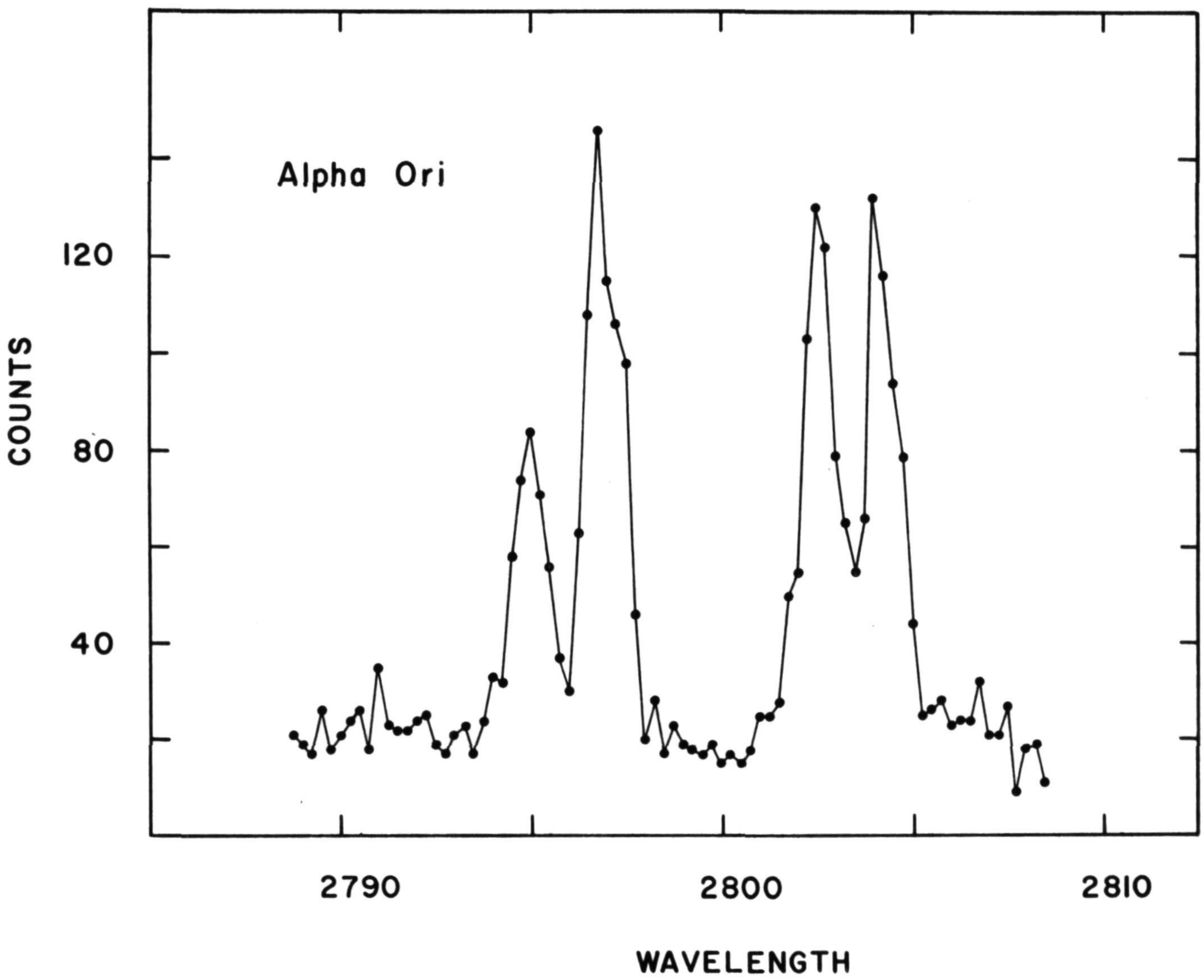

Figure 2. α Ori Mg II Doublet Emission

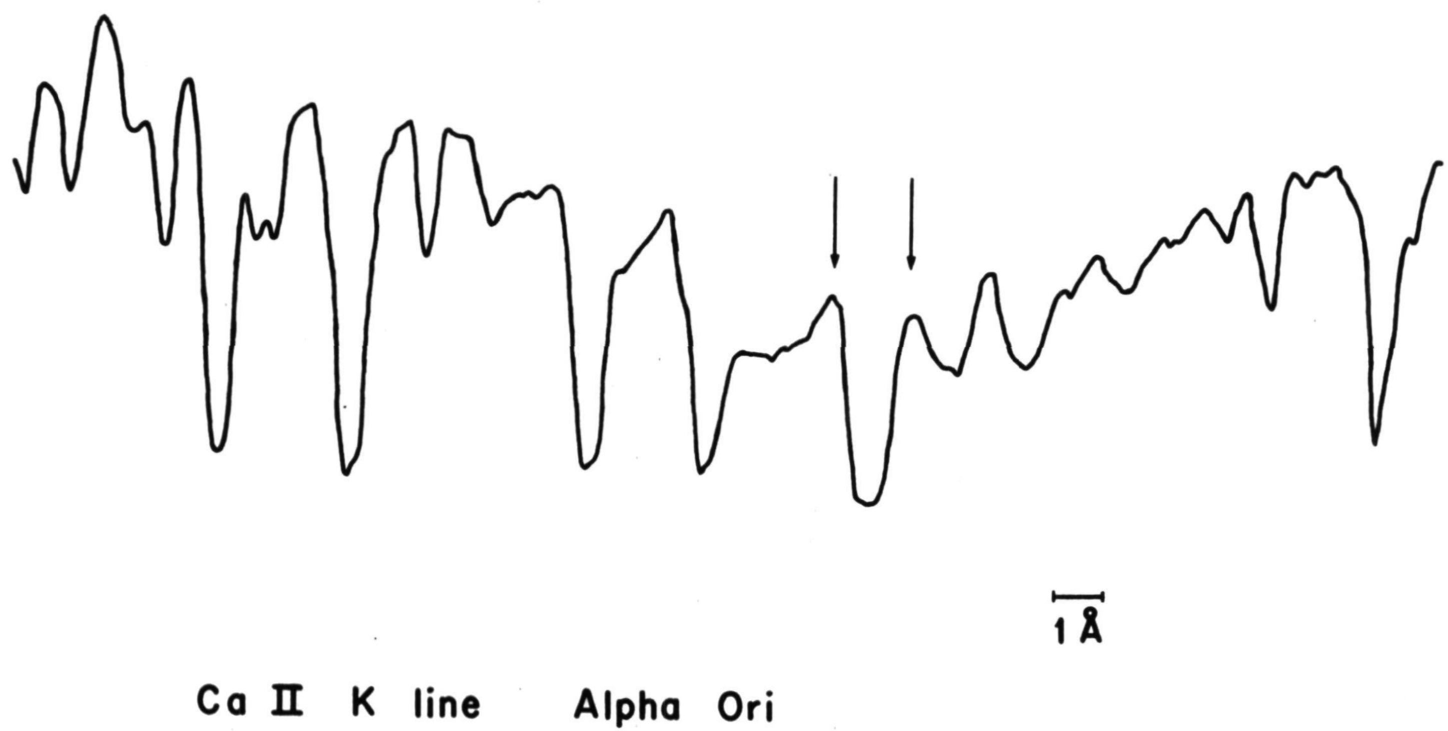

Figure 3. α Ori Ca II "K" Emission

is about 17 times more abundant. The ionization and excitation potentials of these calcium and magnesium lines are such that the Mg II doublet lines are expected to be much stronger than the Ca II doublet, making more feasible the detection of a weak emission at the bottom of the absorption feature. The stellar continuum level at 2800 A is lower than that at 3900-4000 A for stars of spectral types later than A. This may be expected to make detection of a weak emission easier.

Indeed, the Mg II doublet absorption features are shown to be the most prominent spectral feature in the mid-ultraviolet by recent observations from orbiting manned spacecraft (Kondo, Henize and Kotila - 1970; Gurzadyan and Ohanesyan - 1972) and satellite (Lamers, et al - 1973).

The Mg II doublet emission observed in β Lyr and α Ori during the past two flights of the BUSS payload are shown as examples in Figures 1 and 2. The slit width employed for the spectrometer was 0.25 A; the resolution was about 0.4 A. The Ca II "K" line emission in α Ori is shown in Figure 3 for comparison; it demonstrates clearly that the Mg II doublet emission is the more prominent of the two. A comparison between the observed Mg II doublet emission widths and the Ca II "K" line emission widths (Wilson and Bappu, 1957) is discussed by Kondo et al (1972).

The results thus far obtained demonstrate clearly that the Mg II doublet at 2795 and 2802 A are indeed the most prominent spectral features in the mid-ultraviolet. The work by Lamers et al (1974), based on the results from the S59 ultraviolet experiment on the TD1 satellite, shows other interesting mid-ultraviolet spectral features in addition to the Mg II doublet. Although the future space observations will probably reveal other astrophysically important spectral features, the Mg II doublet is likely to remain as among the most significant.

IV. DESCRIPTION OF THE BUSS PAYLOAD

We should next like to present a general description of our instrument and discuss some of the more interesting features of the optical and detector systems. The original payload, shown in Figure 4, was designed and built by Ball Brothers Research Corporation of Boulder, Colorado, in 1971. The payload is about 3.5 m in diameter by 2.5 m high and weighs 540 kg, excluding ballast. Crush pads are attached to the four legs of the lower section or gondola, and the roll cage supplies additional protection to the telescope. The suspension train is composed of a 9.5 mm diameter counterwound steel cable extending some 30 m above the gondola to a 20 m diameter nylon parachute. A 420,000 m^3 single cell polyethylene balloon lifts the package to an altitude of 40 km. Launches are from the National Center for Atmospheric Research (NCAR) balloon base at Palestine, Texas.

The instrument section consists of the telescope, spectrometer, star trackers, and electronics. The instrument is attached to the gondola through a central drive case which carries the elevation and azimuth shafts and their bearings. The telescope is counter balanced on the opposite side of the drive case by the pointer electronics. Three levels of tracking are employed to achieve an ultimate 3" rms tracking error. Initial pointing by magnetometer in aximuth and potentiometer in elevation brings the target star within

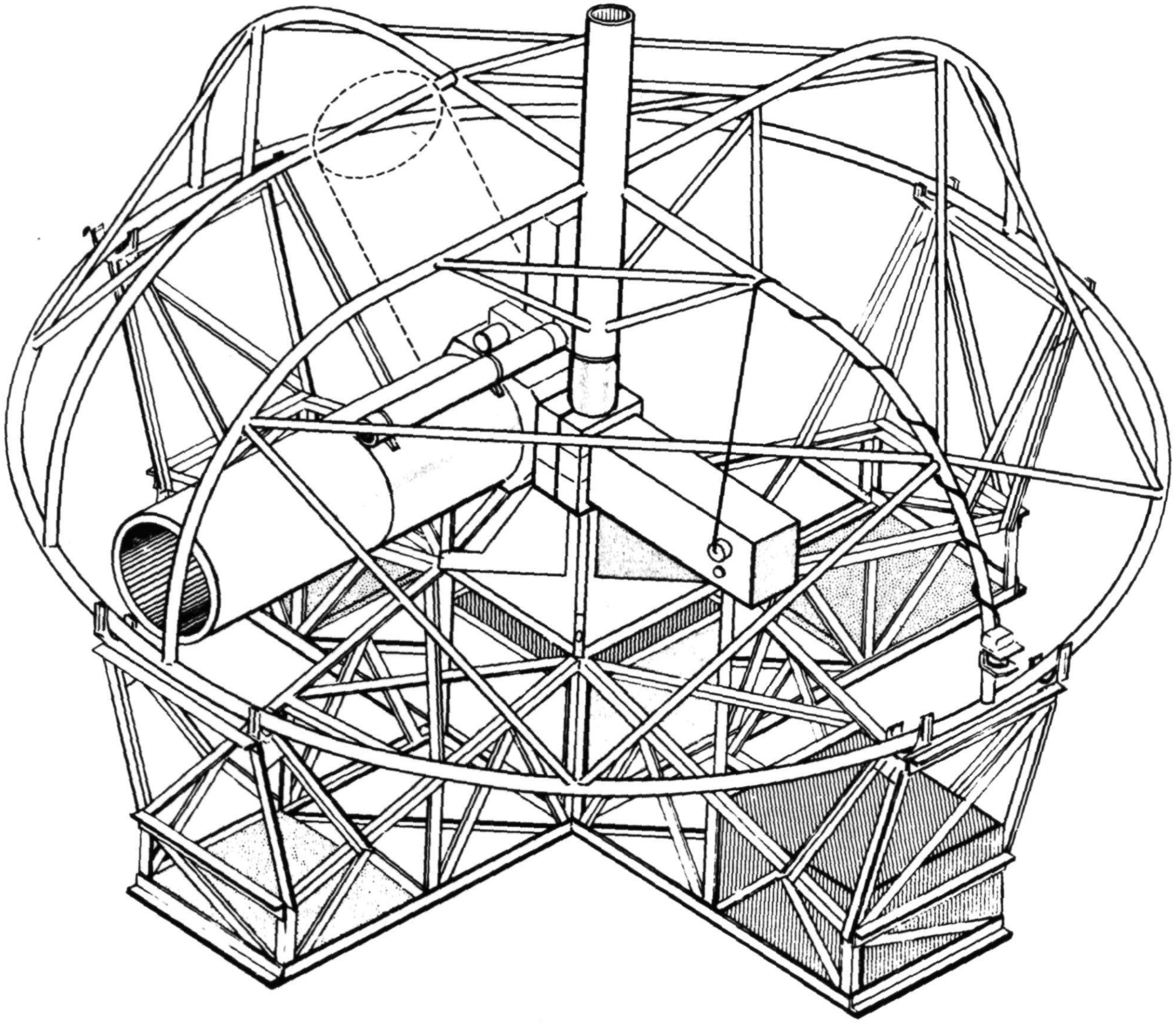

Figure 4. BUSS Payload

the 1^{o} elevation by 3^{o} azimuth field of view of the outer loop star tracker. Payload position data for referencing the magnetometer is provided by NCAR's omega navigation system. The outer loop star tracker is mounted coaxially above the telescope and holds the telescope error to less than 5' with respect to the target star. The 16.5 mm aperture outer loop tracker employs an image dissector, has a range of 4.5 stellar magnitudes, a limiting magnitude of +6 and utilizes magnitude discrimination circuitry to select the desired star from the field of view.

Figure 5 shows a cross section of the telescope and spectrometer. Fine tracking is accomplished by tilting the secondary mirror to reduce object errors of up to 5' to less than 3", effective at the telescope focus. The fine position tracker which controls the secondary mirror is also an image dissector. Control system bandwidths are about 1 hz and 20 hz for the outer loop tracker and the fine position tracker respectively. The telescope is a 40 cm aperture, f/7.5 modified Ritchey-Cretian with servo controlled secondary mirror. The telescope, which uses two hyperboloidal surfaces as in the Ritchey-Cretian, was designed by Bottema and Woodruff (1971) and termed "tilted aplanatic". Object angle errors of up to 10' can be compensated by tilting the secondary mirror to return the image to the optic axis while maintaining a 2" image size. In this design, third order coma is eliminated at the expense of relatively large mirror eccentricities; -0.58 and -12.5 for the primary and secondary respectively (eccentricity of 1 implies a sphere). This makes the fabrication of the mirrors a relatively difficult task. For example, the thickness of glass to be removed at the edge relative to a sphere, in the case of the primary, is 14 μm for a true cassegrain, 17 μm for a Ritchey-Cretian, and 23 μm for the tilted aplanatic. The mirrors were fabricated by Diffraction Limited, Inc., of Bedford, Massachusetts, and performed to the design goal of 2" image size. Both mirrors were made of Cer-Vit and the primary mirror was weight relieved to a weight of 11 kg. The primary mirror is supported on the back side by 3 nylon pads and by 3 spring loaded pads at corresponding points on the front surface of the mirror. About .3 kg is applied to each of the pads on the front surface. The mirror restraints in the radial direction have a slight clearance to allow for thermal changes in the mirror cell. The pads supporting the back of the mirror and the back of the mirror are so shaped that any motion of the mirror is restricted to a rotation about its center of curvature. The secondary mirror is mounted in a flex pivot-gimbal arrangement and controlled by torque motors. The secondary mirror and spider assembly are connected to the primary mirror housing by an invar truss. Mirror alignments have been checked after flight and were found to have remained within the flight limits, through the landing and recovery phases. The fact that the primary mirror was undamaged in an accidental 30 km payload free fall gives a great deal of confidence in the mounting and in the mirror material.

The dichroic filter reflects a 500 A wide band of ultraviolet, centered on 2800 A, into the Ebert-Fastie spectrometer and transmits over 80% of the visible light to the fine position star tracker. The f/7.5, 0.5 m focal length spectrometer is basically an Ebert-Fastie type utilizing a 2160 grooves per millimeter grating in second order to achieve a dispersion of 3.3 A/mm.

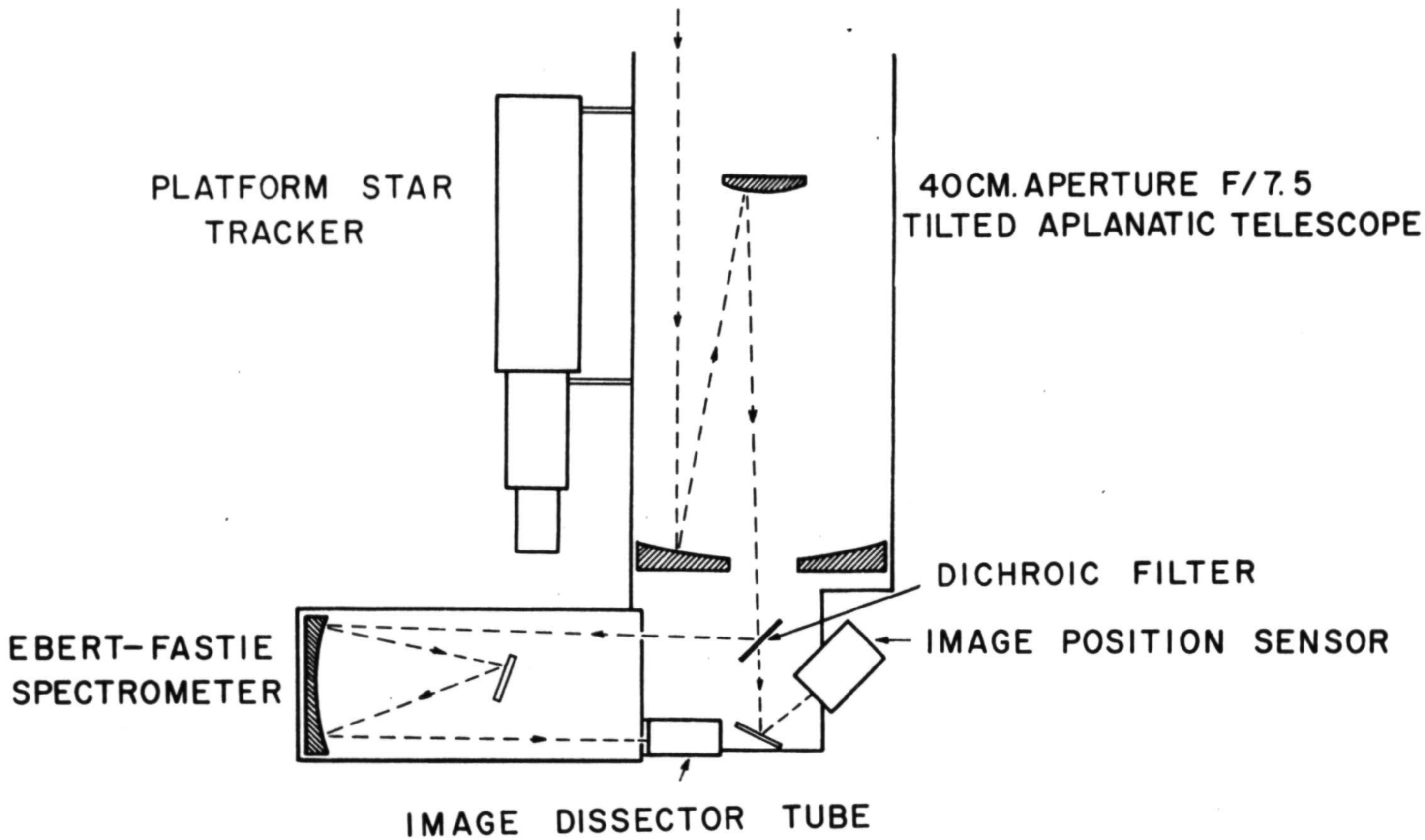

Figure 5. BUSS Instrument

In the spectrometer design a compromise was made allowing a small amount of coma in order to reduce the image height (Bottema, Ray, Wells - 1972). The rectangular envelope of the image is approximately .027 mm by 0.47 mm. A 50 A wide spectrum, centered on 2800 A is scanned in 1/4 A increments by an ITT type F4012 image dissector operated in the photon counting mode. System resolution is about 0.4 A. An onboard programmer provides several scan routines as directed by telemetry from the ground station. The number of events accumulated in each 1/4 A channel is telemetered sequentially to a CRT display in the ground station. The image dissector employs a 17.5 mm diameter extended S-20 photocathode on a quartz face plate and a mechanical aperture .072 mm wide by .9 mm long. The length of the aperture is oversize to allow for azimuth tracking errors which are slightly larger than in the elevation or dispersion direction. Advantages of the image dissector are the accuracy and speed of electronic scanning and the low noise resulting from the small effective photocathode area. With discriminators set for 85% counting efficiency, we attain a dark count rate of less than 4 per second at room temperature and less than 0.2 per second at 0^oC for our effective photocathode area of 0.065 mm^2. For our slit dimensions, we have obtained a resolution within a few percent of the theoretical value for a scanning rectangular aperture. This is made possible by high performance magnetic focusing of the photoelectrons. Although we have been pleased with the reliability and performance of the image dissector, there are several features related to the focus coil which require special attention. First, the power dissipated in the focus coil, if not minimized by proper design, can cause the tube to operate at higher temperatures resulting in a larger dark count. With our nominal 2.5 cm diameter tube the power dissipation is about one watt. We have found it undesirable to lower the power by shortening the coil, as the electron optical resolution suffers. Depending on the axial position of the coil, positive or negative electron image magnification may be observed, especially in the case of shorter coils. Since some high performance coils employ slight magnification, this should be taken into account in choosing the size of the mechanical slit. Another characteristic worth mentioning is the necessity of adjusting the focus current as the electron image is deflected, in order to compensate for the curved electron optical focal surface. This compensation typically amounts to a decrease in the focus current of a few per cent. Generally a focus current regulation of better than 0.1% is required if maximum resolution and deflection accuracy are to be maintained. It is also generally helpful to shield against the earth's magnetic field. The only serious disadvantage of the image dissector is that only one data channel at a time is observed. For an extended number of resolution elements, it may be desirable to go to a multichannel detector at the expense of greater cost and complexity.

We should now like to make some brief comments about the reflective coatings on our optics. Because of the generally adverse field conditions encountered in ballooning operations, we have found it highly desirable to use durable, easily cleanable coatings. All of our coatings are multilayered dielectric and comply with military environmental specifications. Reflective coatings on the telescope mirrors have an enhanced ultraviolet reflectivity of greater than 95% and a visible reflectivity of greater than 80%. The dichroic filter and spectrometer mirror have the same coating which has a reflectivity of 98% within 100 A of 2800 A, and less than 15% in the visible spectrum. This provides a rejection ratio of about 300 for visible light. When further reduction of visible light is necessary additional filters can be inserted at the telescope focus. Visible transmission is about 85%.

V. FUTURE PLANS FOR THE BUSS PROJECT

Current plans for improving the BUSS payload lie in three general areas: (A) Extension of the spectral coverage to the entire middle ultraviolet region, i.e. 2000 - 3400 A; (B) increasing the spectral resolution to at least 0.1 A and possibly to 0.03 A; and (C) improving the star tracking capability to track stars as faint as 10th magnitude through the use of off-set guidance techniques.

We expect to realize the indicated range and resolution in a cooperative venture with the Space Research Laboratory of the Astronomical Institute, Utrecht, the Netherlands. They have designed an echelle spectrometer which will be combined with an SEC vidicon detector and attached to our telescope and tracking systems. A television-type sensor, because of its two dimensional format and storage capability, makes possible the simultaneous observation of all resolution elements in the spectral range. This type of detection ameliorates the trade-off among spectral range, resolution and observing time, which has been a major problem in spectrophotometric observations from space.

As an alternative means of obtaining the same, but somewhat less ambitious, objectives, we are investigating the employment of a one-dimensional multichannel sensor such as a silicon diode array.

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DISCUSSION SUMMARY — PAPER 2.6

The UV spectrophotometer has programmable routines. For example, the dwell time per channel can be programmed for a fixed time or for a fixed number of counts.

It was reported that the 2-percent efficiency referred to in the instrument description was the ratio of photons detected to photons incident within the bandpass.