Session 7

Photometry from Space

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R.C. Bless and M. Taylor

Astronomy Department, University of Wisconsin-Madison, U.S.A.

Abstract

After a brief review of the traditional opportunities as well as the problems of doing photometry from space vehicles over a wide variety of wavelength regimes, several topics will be discussed. These include the factors associated with various types of spacecraft orbits (for example, near-earth, geosynchronous, planetary cruise) and with the different kinds of vehicles and platforms used (expendable, shuttle attached payloads, permanent stations, multi-purpose spacecraft, small and large projects). Since ground-based capabilities are constantly improving and expanding, it is necessary to assess those that might compete with space-based photometry. Finally, the present state of space observations as they pertain to "classical," high precision, high speed and multi-object photometry will be reviewed; possibilities for the future will be addressed briefly.

1. Introduction

This is an extremely broad topic encompassing not only a wide range of wavelengths, but a wide range of techniques as well. Even if we were not limited by the length of this paper, we would certainly be limited by our ignorance. However, we hope to address most of the broader issues of space photometry as well as a few of the more interesting and specialized developments of late.

We realize that not everyone at this meeting is an expert in space astronomy and so, we will begin with a brief review of the advantages and disadvantages of doing photometry from above the earth's atmosphere. In this context, we will also consider some of the astronomical implications associated with various types of vehicles and their orbits. The ultraviolet part of the spectrum has probably been the primary beneficiary of space photometry to date. Consequently, we will take a look at the evolution of UV photometry over the last 25 years or so. This will bring us up to the present time of the Hubble Space Telescope (HST) where three of the five instruments currently installed are capable of doing photometry: the Faint Object Camera (FOC), the High Speed Photometer (HSP), and the Wide Field Camera (WFC). We will end with a discussion of what we perceive are the primary areas of concern for space photometrists today.

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2. Brief review of characteristics of space

The opportunities afforded photometry by space are well-known and are all a direct consequence of the absence of the earth's atmosphere. These advantages can be divided into three major areas:

1) Access to the entire electromagnetic spectrum: From the ground, we have access to the visible, almost all of the radio, and a few narrow regions in the infrared, primarily in the near-infrared. As is well known, the amount of absorption by the earth's atmosphere decreases with increasing altitude. In this vein, we might mention the south pole as a potentially good site for photometry. The south pole is more than 3000 m above sea level and the air there is very cold and dry opening up new "windows" in the IR part of the spectrum. These features are currently being exploited by the Center for Astrophysical Research in Antarctica (Harper 1991).

2) No scintillation and no changes in atmospheric transparency: Other papers presented at this meeting (e.g. Dravins et al. 1992) have addressed the problems associated with scintillation. However, for completeness, we will mention that the absence of the earth's atmosphere in this regard becomes very important in the search for small amplitude oscillations which occur on timescales of minutes to microseconds. Scintillation and photon noise are the two major sources that usually limit the photometric accuracy of fluctuations which occur on timescales of less than one minute while atmospheric transparency fluctuations limit the photometric detectability of variations on longer timescales (Warner 1988).

3) Reduced background: The elimination of atmospheric turbulence allows space photometrists to use smaller apertures and hence, significantly reduce the background noise. This is particularly beneficial in the infrared. From the ground, the IR sky brightness increases drastically with wavelength as a result of airglow and/or thermal emission from telescope optics and other components of the telescope (Joyce 1992). From space, the angular resolution of an object is limited only by the optics of the telescope, the properties of the detector, and the capabilities of the pointing control system. Hence, it will be much easier to discern small intrinsic variations which occur in the IR. During this meeting we have heard about the capabilities of image restoration and active optics (Shearer et al. 1992), but, at least in the case of active optics, we are limited to small fields of view.

The advantages of doing photometry from space however, do not come without a price. The difficulties include at least the following:

1) Environmental effects: These include the low temperatures in space, the temperature changes which occur over the day-night cycle, and radiation by trapped particles which can potentially damage detectors and other sensitive electronics. We will say more about this in section 4.

2) Spacecraft limitations: These limitations include restrictions on launch load which in turn affect the orbits which are achievable for a specific vehicle plus payload. Also, limitations on the power available to operate an instrument, limitations on the rate at which data can be sent to a ground-station on earth, and quality of the pointing control system are all concerns to be dealt with. On a slightly different note, scheduling space observations, especially those that are time-critical has certainly proven to be a non-trivial problem as has the determination of the precise universal time of an event which is known only as well as the calibration of the on-board clocks.

3) Political: The cost of putting an instrument into space is extremely high and consequently, politics plays a significant role. Budget problems often make it difficult to proceed on a reasonable time-scale. As a result, space astronomy suffers from long lead times and delays which can result in flying obsolescent equipment. (The spacecraft computer on HST is based on 1970's technology!). Finally, oftentimes, one has a large and cumbersome bureaucracy to deal with and, at least in the U.S., there is always the possibility of outright cancellation of a project. These aspects of space astronomy are not well suited for a university environment where one hopes to train the next generation of space astronomers.

Several other factors affect astronomical performance in space. Many of these can be categorized according to the various kinds of orbits into which a variety of vehicles can be placed. First the types of orbits:

1) Near-earth (orbital periods of roughly 100 minutes): Because of periodic earth occultations and the necessity to avoid the South Atlantic Anomaly (SAA), the observing time per orbit is severely limited. In addition, scheduling time-critical observations can be difficult because half of the time you may be on the wrong side of the earth. Commanding and data storage are more complex because one must rely on a communication satellite such as TDRSS or have more than one ground station available. Real time commanding must be scheduled in advance to insure TDRSS availability. With HST, these factors, taken together with a cumbersome ground system, have so far limited the actual (collecting photons from the program object) observing efficiency to about 10 percent, or about 10 minutes per orbit, on average.

2) Geosynchronous orbit (more generally, 24 hour orbit): More energy is required to reach the required altitude, but IUE has demonstrated the huge advantages of this type of orbit. The spacecraft can be in contact with one or another ground station for long periods of time so that data are immediately available and commanding can always be done in real time. Further, the earth subtends a much smaller angle than it does in near-earth orbits with a corresponding increase in observing efficiency. It seems to us that more serious thought should be given to the trade-off between payload size and observing efficiency than has heretofore been done, at least in the U.S.

3) Planetary cruise (for example, Voyager): Typically, these orbits offer lots of observing time, but the available power and hence, bandwidth is usually limited. The slower data rate is a concern for at least some science programs. Also, instruments for planetary work often are not optimal for stellar observations.

Let's turn next to a few considerations about launch vehicles.

1) Sounding rockets: These are relatively low-cost vehicles which provide an opportunity to test novel ideas or techniques. Although the amount of observing time is limited, sounding rockets enable the scientist to have maximum control of a project and they are an excellent way to introduce students to space science.

2) Attached payloads (i.e. space shuttle): The situation for larger vehicles is not as happy. In an ideal situation, there should exist a stable of launch vehicles capable of placing a wide variety of payloads into the orbit most appropriate for the mission. That is, the scientific and observational requirements should drive the choice of vehicle rather than the other way around. In the U.S. at least, this has not been possible since for political reasons, the orbiter was to be the all-purpose launch vehicle. The problems of this policy are many, but the chief one is that any man-involvement complicates matters enormously with little, if any, advantage. Nor is the orbiter a good platform for an attached payload requiring accurate pointings. The ASTRO payload is a good example. The pre-mission planning was an enormous task since a new timeline and associated mission products (which were numerous, in part because of the logistics involved in a manned flight) had to be developed for each new launch date which differed by more than a few weeks from the previous date. In the case of ASTRO, there were thirteen different timelines, none of which was used during the actual mission because of problems early-on. One of the chief lessons learned from that mission is that the space shuttle is not a good vehicle from which to do space astronomy when scheduling is time-dependent.

3) Expendable vehicles (for example, Titan or Delta): Even if the most expensive of these vehicles approaches the cost of a shuttle launch, they are unmanned and

consequently the logistics of these missions are considerably less complicated. NASA has long been urged to use expendable vehicles to launch scientific satellites, and it seems to be moving in that direction, albeit slowly. An interesting development which we will comment on later is the Pegasus launch vehicle.

4) Space station/Lunar base: As with any of its very large programs these mega-projects are more the product of NASA's concern with its institutional survival than with science. Furthermore, they are so far in the future, so enormously expensive, and so subject to budgetary as well as technical forces that we find it difficult to consider them as significant opportunities for anyone out of diapers.

3. Some highlights of UV photometry

Space photometry has been evolving over the last several decades with substantial efforts directed toward UV astronomy. This region of the spectrum was first explored with sounding rockets, but, it was quickly realized that longer missions were required in order to begin to understand the UV universe. In 1968, the second of the Orbiting Astronomical Observatories, OAO-2, was launched, three years after the quick failure of the first OAO spacecraft. Although characterized as an engineering flight with limited expectations, it lasted 50 months. It consisted of several 0.3 - 0.4 m telescopes with a 10' field of view (Code et al. 1970), indicative of the quality of the pointing control system. OAO-2 did broad-band filter photometry and low resolution spectroscopy with a photometric accuracy of on average, a few percent.

Among the subsequent UV missions was the Netherlands Astronomical Satellite (ANS) launched 2 years later. Again, the telescope aperture was small, 0.23 m, and the field of view, although smaller than that used in OAO-2, was still quite large, 2.5' (Wesselius et al. 1980). The broad-band photometry obtained with the ANS had a photometric accuracy of < 1 percent.

In 1978 the International Ultraviolet Explorer (IUE) was launched. Although designed to last only a few years, it has been operating for almost fifteen years! The telescope is a 0.45 m with a 10" x 20" aperture which has both a high and a low resolution spectrograph (Boggess et al. 1987). The photometric accuracy of the IUE over the entire bandpass from 1150 to 3200 Å is between 5 and 10 percent.

This brings us up to the present time of the HST. As mentioned earlier, three of the five HST instruments are capable of doing photometry. Each instrument has narrow, medium, and broad-band filters spanning the ultraviolet and optical regions of the spectrum. The FOC is capable of doing photometry at the few percent level, while the WFC I obtains optical photometry with an accuracy of 5 - 10 percent. The WFC I is not able to do photometry in the ultraviolet because of contamination build-up on the CCD. Although the HSP was originally expected to do 0.1 percent photometry on a routine basis, the spherical aberration of the HST mirror and the instability of the pointing system (jitter) have made that impossible. With 15 percent of the encircled energy contained within a 0.1" radius, compared to the original specification of 70 percent, the HSP can only do about 10 percent absolute photometry; this is the accuracy to which observations taken months apart can be intercompared. The HSP's real strength with the current state of the HST is in doing very high time resolution relative photometry.

Unfortunately, with the degraded images of the HST and the pointing instability, space photometry doesn't look much better than it did 25 years ago. Of course, there is still the possibility that the situation will improve with the second generation instruments and with the installation of COSTAR, an instrument designed to minimize image degradation resulting from spherical aberration. Unfortunately, this will be accomplished at the expense of the HSP.

4. Detectors in space

Given the many well-known advantages of CCDs over other detectors, together with the increasing read-out speeds, CCDs are becoming attractive for all but the highest speed photometry. However, there are a couple of areas of concern.

As mentioned earlier, radiation effects from trapped particles can be a serious problem. Not only can they add noise to the data, they can permanently damage portions of the detector or associated electronics. Although no permanent radiation damage has yet been detected, WFC I sees about 5000 hits per 800 x 800 CCD within 45 minutes. Generally, these cosmic rays affect individual pixels and so when half of the radiation from ST was to fall within one pixel there would have been a problem in distinguishing particle "stars" from real stars. With the spherical aberration, however, the image covers so many pixels that this effect is not seen. However, the chances of a particular star being contaminated with a cosmic ray hit is higher. In order to ease the data analysis, WFC I routinely takes two images of every field. We might just add that WFC II will use thicker CCDs than those used in WFC I, so not only will more energy be deposited by a cosmic ray, but the resulting electrons will diffuse to a larger number of pixels and could form faint blotches in an image.

Another major concern for CCDs in space has to do with obtaining flat fields. Unfortunately, there are no good, natural flat field sources. Although WFC I uses the earth as its flat field source, clouds produce streaks on the images and ocean waves produce very bright glints. In order to minimize these problems, WFC I takes a median of several flats at different orientations of the HST. WFC II will have its own internal lamps and optics to provide flat fields. However, earth flat fields will still be necessary in order to remove the signature of the optics ahead of the camera.

a. UV Photometry with CCDs

Although WFC I can do photometry in the visible at the 5-10 percent level, depending on how crowded and how large the field is (the point spread function is not constant over the entire field), because of severe contamination by an unknown source it cannot do UV photometry. Contaminants adhere to the coldest surface available, and in the case of WFC I, this is the CCD. Since it takes only a mono-molecular layer of organic material to absorb UV radiation, contamination is a very serious problem at these short wavelengths. WFC I loses its UV sensitivity in a matter of hours after the CCDs are heated sufficiently to evaporate off the contaminants. It has been estimated that to work well in the UV, the rate at which contaminants are deposited on the camera will have to be at least five orders of magnitude less than the rate seen in WFC I. This means that for cold CCDs intended for use in the UV, contamination has become a major problem at a level that has not been faced before. Although the source of these contaminants is not yet known, a huge effort has been made to eliminate all potential sources of contamination for WFC II. In addition, the CCDs on WFC II have considerably lower dark currents than those on WFC I and so will be able to operate at slightly warmer temperatures, -70C rather than -90C. In any case, if CCDs are to be useful in the UV this problem must be solved.

Another problem with using CCDs in the UV has to do with the red leak in interference filters. Observing the UV radiation from a cool star, for example, is difficult because the visible light leaking through the filter, combined with the high quantum efficiency of CCDs in the red, can swamp the UV signal. To overcome this problem, the Jet Propulsion Laboratory (JPL) has undertaken a project to produce so-called Wood's filters which are based on a discovery by R.W. Wood in the 1930's that alkali metals absorb UV radiation but have a long wavelength cut-off set by the plasma frequency of free electrons. Although these characteristics have been known for more than 50 years, the challenge comes in manufacturing stable filters of this type which can survive in the space environment. Recently, JPL has been successful in producing Wood's filters which will be used for WFC II. A transmission curve for one of these filters comprised of a sodium layer 6000 Å thick deposited on MgF_2 substrates has a peak transmission of about 30 percent and is blind to radiation longward of about 2200 Å at the 10^{-5} level (Clarke et al. 1992). Despite their low transmission, these filters could be useful in UV applications and in fact, might be excellent dichroic filters.

b. IR photometry with CCDs

Compared to other wavelength regions, very little IR photometry has been done from space. The biggest problem from the ground has to do with the large backgrounds and hence the difficulty in discerning small variations. Also, IR detectors are more complex than optical CCDs (Glass 1992). Optical CCDs are capable of doing 0.1 percent photometry. Data of similar accuracy should be achievable in the IR as well. However, because of the large IR backgrounds, it is necessary to get above the earth's atmosphere before one can hope to be competitive in this regard. The Infrared Astronomical Satellite is so far the only satellite designed to do IR photometry and the accuracy obtained was only on the order of 10 percent or so.

IR detectors have seen tremendous advances over the last several years and we will no doubt continue to see them evolve. The two areas that will probably see the greatest improvement are the size of the detectors and the read noise. The largest

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IR CCDs being built today are 256 x 256 pixels with typical read noise values on the order of 100 electrons. The CCDs being developed for the second generation HST instrument NICMOS will have lower read noise. These arrays will operate over a wavelength range from 0.7 - 2.5 μm with a linearity to about 150,000 electrons. The read noise of these arrays is down by a factor of 4; 25 - 30 electrons (Thompson 1992). We expect to see continued progress in this area over the next few years.

c. X-ray photometry with CCDs

We would next like to touch briefly on some interesting new developments in the x-ray regime. X-ray detectors are generally quite efficient; the problem has been in their energy resolution, that is, the width of their "filters." The workhorse detector has been the proportional counter which absorbs a large fraction of the incident photons. The amplitude of the resulting pulse is proportional to the energy of the detected photon giving an energy resolution of typically 25 percent of the energy. This corresponds roughly to optical broad-band photometry, like UBV. Below 1 keV the resolution becomes very poor, however. Here atomic absorption-edge filters–for example, beryllium, boron, and carbon–are used to isolate broad energy bands. The transmission of these filters can be measured and the counter gas stopping efficiency can be calculated to give a calibration good to about 5 percent.

A considerable step up in energy resolution is provided by CCDs specially processed for use as x-ray detectors. In order that an x-ray photon is absorbed, the depletion regions are made 10-20 times thicker than for optical CCDs. The energy resolution of such a CCD is about 100 eV at 6 keV, significantly better than that of a proportional counter. In optical terms, this corresponds very roughly to Stromgren photometry. The efficiency of such a detector is very good; in fact, from 0.5 to 8 keV, the CCD is nearly 100 percent efficient. Two 4 x 4 CCD arrays each with 512 x 512 pixels made at MIT are to be flown on the Japanese-U.S. ASTRO-D satellite in February 1993.

The resolution of a solid state detector is limited by the statistical nature of the ionization process which is only about 30 percent efficient. One technique to achieve higher energy resolution is not to measure the charge produced by an absorbed photon, but to measure the temperature rise it produces in a small (say 0.5 mm square and a few tens of microns thick) silicon element which acts like a calorimeter. For this purpose the detector must be at a very cold temperature, 50 mK. Such a detector made by McCammon (1987) at U. Wisconsin gives an energy resolution of about 1000 at 6 keV. This is narrow band photometry indeed, corresponding to narrow line filters in the optical. X-ray photometry is in the happy situation of having available extremely sensitive detectors with a wide range of resolutions.

5. Future prospects for space photometry

There are some very promising projects for the future of space photometry.

1) HIPPARCOS: Although the primary goal for HIPPARCOS is to measure accurate stellar parallaxes, a separate instrument called Tycho will be obtaining on average, 150 photometric observations of each of about 1,000,000 stars. Although the expected photometric accuracy is only on the order of 30 mmag for the brightest stars (Großmann, 1992) it will provide an enormous data base of photometric observations.

2) PRISMA: If funded, this European project will be a dedicated mission designed to exploit the long observing times available from a geosynchronous orbit. The primary objective of PRISMA is to do asteroseismology of solar-type (and later-type) stars. In addition, observations of classical pulsators, such as the δ Scuti and RR Lyrae stars, Cepheids, and rapidly oscillating Ap stars, will be obtained (Bromage 1992).

3) Pegasus: A third prospect for the future has to do with the development of a new, small, expendable launch vehicle in the U.S. called Pegasus. Pegasus is dropped out of a B-52 and then fires a two-stage rocket to reach its orbit. This is a very low-cost operation, but the project has not seen success as of yet. There have been two launch attempts, both of which have had problems. A third attempt is currently being scheduled for the end of this year to launch the X-ray satellite Alexis.

In summary, how do we see the future of photometry from space? We certainly have the technical capabilities to successfully do photometry from space: 1) we have the expertise required to build optical systems which produce very good images, 2) pointing control systems have reached a sophistication that enable the use of small apertures, and 3) a wide variety of sensitive detectors are now available or soon will be.

The cost and time required for the construction of space missions must be reduced. Long dry spells during which no new data are being acquired must be avoided. To this end, it seems to us that more emphasis should be put on several smaller, special purpose payloads rather than on a single, large, all-purpose satellite intended to do many different things. Large projects of course have their place, but they should be carefully justified as the only way to obtain crucial data. Furthermore, it should be assumed that missions will be designed for high orbits unless some compelling factors justify the serious loss of operational efficiency associated with a low orbit. Finally, greater discipline must be imposed such that a mission is descoped if cost and schedule constraints are exceeded, rather than dragging on interminably.

Even if all of these suggestions were implemented, many programs would still be very expensive. Given the forseeable fiscal constraints under which most of the nations having space programs will have to live, there will likely be a need for international cooperative efforts. Such programs can become very complex and cumbersome. We must learn how to work together effectively.

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Discussion

D. O'Donoghue: *Will the Prisma mission be devoted to doing stellar seismology of solar-type stars?*

Taylor and Bless: Yes. the Prisma mission will do stellar seismology of solar-like stars and others. There will be a talk this afternoon when we will hear much more about the specific goals of the Prisma project.

C. Morossi: *Could you comment on damage in UV coated CCD's due to particle radiation?*

S.B. Howell: It depends on where the event hits the CCD. For example, if a radiation event destroys or damages part of the serial output register, all pixels which pass through the affected part of the output register, will be affected; possibly a large part of the array. If however a pixel in the imaging array is damaged only those pixels in the column below it are affected. Some radiation events which *damage* pixels appear to *fix* themselves on timescales of months, probably due to charge, initially deposited deep within pixels, finally let out.