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Backyard spectroscopy and photometry of Titan, Uranus and Neptune

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Abstract

We present and discuss observations of Titan (photometry and spectroscopy) and Uranus and Neptune (spectroscopy only) obtained using off-the-shelf equipment, affordable and available to many amateur astronomers and small colleges. Spectral observations compare well with published results from front-line observatories, and some evidence of seasonal change is evident in both spectra and narrowband photometry. Scattered Saturn light presents a significant problem for Titan observations, in particular, for slitless spectroscopy, and our attempts to reproduce Titan's lightcurve have so far been unsuccessful.

1. Introduction

The outer planet atmospheres are dynamic objects whose full understanding requires constant monitoring. Although much of our understanding of them derives from the detailed, but brief, observations during the Voyager encounters and more recently by spaceborne observatories and large ground-based telescopes with advanced adaptive optics systems, there remains much to be gained from simple disk-integrated observations. The aim of this paper is to highlight and demonstrate those measurements likely to be of most use, rather than to be a guide to observing techniques per se.

As an example, Titan's photometric variability was known from historical compilations (e.g. Andersson, 1977) of earlier observation, but significant progress was not made until systematic monitoring by Wes Lockwood and colleagues at Lowell Observatory—using a modest telescope, but one dedicated to obtaining a consistent photometry dataset of the outer planets and Titan over some 30 years, a dataset which has helped understanding of Titan's seasonal cycle (e.g. Lockwood and Thompson, 1999; Lorenz et al., 1997, 1999).

Titan's spectrum is very distinct from that of stars and other planetary satellites in that it shows strong methane absorption bands. These were responsible for Kuiper's discovery of Titan's atmosphere in 1944. Spectrophotometric measurements in the near-infrared generated a 'modern' Titan spectrum as early as 1967 (McCord et al., 1971) but it was only in the early 1990s that it was realized that Titan shows short-term variability in the near-infrared, in the windows between methane bands. Noll and Knacke (1993) using data from Cruikshank and Morgan (1980) augmented by data of their own noted some systematic variation of near-infrared brightness with longitude; Lemmon et al. (1993) independently showed that Titan's spectrum in the windows is brighter on Titan's leading hemisphere. Coustenis et al. (1995), Griffith (1995) and Lemmon et al. (1995) confirmed these results. Coustenis et al. (1995), Griffith et al. (1991) and Lemmon et al. (1995) applied haze scattering and methane absorption models to attempt to derive surface reflectivities (and thereby constrain surface composition) using these data.

Titan, whose near-infrared lightcurve was ostensibly reasonably well known, appears to have variations in albedo that are not correlated with longitude and are interpreted to indicate cloud activity (see Fig. 1 and Griffith et al., 1998). Only continued monitoring permitted the detection of anomalous brightening attributable to weather activity (Griffith et al., 1998, 2000).

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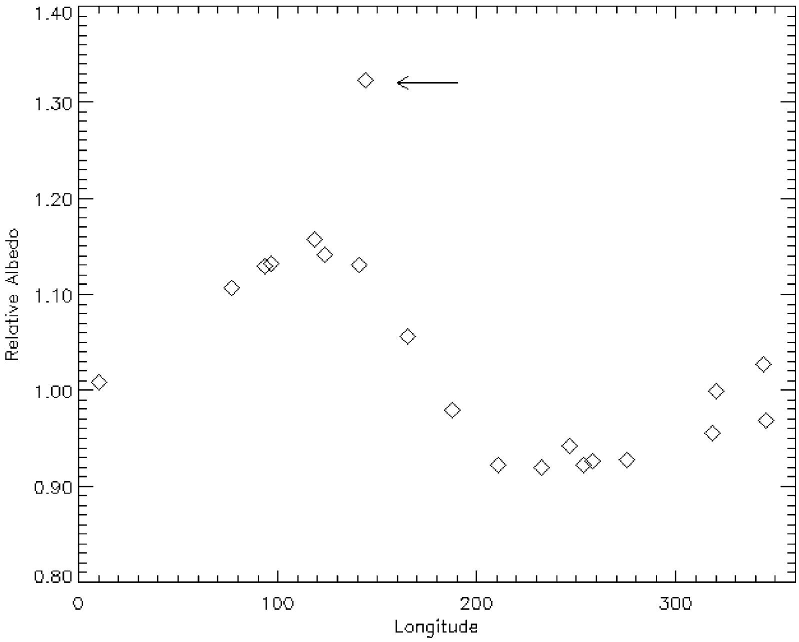

Fig. 1. Titan's rotational lightcurve, from a summary figure by Griffith et al. (1998). The leading hemisphere is around 25% brighter than the trailing hemisphere. An anomalous datapoint (arrowed) corresponded to an observation where spectral fits and the albedo at 3 μm indicated the presence of a cloud covering ∼ 10% of Titan's disk in 1995.

As professional observers of these objects will know only too well, it is difficult to persuade the Telescope Allocation Committees of front-line facilities to permit long-term monitoring projects in the hope of perhaps seeing some changes. This kind of monitoring exercise, requiring tens of nights of observations per year (yet perhaps only a few minutes per night), can only be implemented in an efficient manner through 'service' observing where a target list is followed by operators, without requiring a principal investigator to be physically present or to be allocated the whole night. It is therefore fruitful to explore what can be done with more modest facilities (see Fig. 2), that may be available at small educational institutions or even in the hands of individuals. An advantage of a distributed network of observers is that longitudinal coverage is enhanced, and monitoring is less susceptible to disruption by weather at a particular site.

Many organizations exist which support and encourage amateur observations, such as the Association of Amateur Variable Star Observers (AAVSO), Association of Lunar and Planetary Observers (ALPO), the British Astronomical Association (BAA). In the areas of variable star observing, and supernova detection, these organizations are well established as major contributors. In planetary science, the International Occultation Timing Association (IOTA) has successfully collated amateur observations to obtain otherwise unobtainable datasets, a good example being the 1989 occultation of Titan by 28 Sag.

Since that time, considerable improvement in the capabilities of home computers and in the availability of reasonably priced CCD cameras (driven largely by camcorder requirements) have put sensitive instrumentation in the hands of many amateur observers. Further, the explosion of the internet has made it far easier for like-minded amateurs to contribute observations to a common database and to follow up targets of particular interest. A relatively recent capability that has evolved is that of amateur spectroscopy, using a CCD camera as the detector. Excellent and readable introductions to the topic are given by Kannappan and Fabricant (2000) and Mais (2002).

In this paper we demonstrate the utility of spectroscopic and photometric measurements of Uranus, Neptune and Titan. These three objects in particular are of interest in several respects. First, they are bright enough to permit small telescopes to gather useful signal. Second, there is already ample evidence of seasonal or shorter-term changes on them. And third, the objects are small enough in angular size (Uranus only just) to permit useful observation with simple slitless or objective-prism spectroscopes. Our observations are made using simple slitless non-objective spectrographs (West and Alexander, 2001), although similar or better results could be obtained with other designs such as fiber-optically coupled spectrographs (Glumac and Sivo, 1999—see also www.sivo.com) or conventional slit instruments such as the Santa Barbara Instrument Group (SBIG) spectrograph (Gavin, 2000—see www.sbig.com) and that constructed by one of us (Fujii—see Table 1).

The three objects described in this paper follow a progression of increasing difficulty. Uranus is (at 6th

Fig. 2. Author Doug West with observing equipment. Modern computer-guided telescopes can be set up within a few minutes, making a permanent observatory installation largely unnecessary. For monitoring projects the small manpower overhead in setup outweighs the larger aperture of mountaintop observatories.

magnitude) by far the brightest of the three, and easily identified against the stars by its perceptible disk. Neptune is considerably fainter (8th magnitude) and smaller, and is perhaps most easily identified in a star field by its spectrum. Finally, Titan is of comparable faintness to Neptune, but its spectrum must be pulled out of a much brighter background due to scattered light from Saturn. This effect is a particular issue for small telescopes.

2. Spectroscopy of Uranus

Fig. 3 shows a spectrum of Uranus obtained with amateur equipment in RL's home backyard. The site is approx. 2 km East of the University of Arizona at an altitude of approx. 800 m. The equipment used was an alt-az mounted Schmitt–Cassegrain Telescope (SCT) with a 20 cm aperture (Meade LX200 8″). The detector was a commercial 512×290 CCD camera (Starlight Express MX5) with a 4.9×3.6 mm^2 chip, a built-in Peltier cooler and 16-bit digitization, read out via a parallel interface to a laptop computer. A blazed 200 line/mm diffraction grating (Rainbow Optics Star Spectroscope) was placed in the optical path to operate as a slitless spectroscope. The telescope, camera and grating cost about $2500 (although mechanically lighter but optically equivalent telescopes are around half of this cost), $1000 and $200, respectively. The exposure time was 60 s.

The grating, equipped with a screw thread, was attached to the front of the camera as would an ordinary optical filter. The grating is therefore some 4 cm or so in front of the CCD chip, and the dispersion such that the zeroth-order image of the object under study, and its first-order spectrum, cannot both fit on the image. For bright objects, this is not a significant obstacle, since the source of the spectrum can be readily identified. An alternative approach requires some machining to place the grating closer to the chip. Some trial and error is needed to adjust the orientation of the grating such that the dispersion occurs along rows of pixels, which is most convenient for data analysis. The grating could also be inserted in a filter wheel.

Tracking glitches and field rotation of a few pixels tend to occur in alt-az tracking mode with exposures longer than about 1 min. Since the observation cycle (acquisition, download and inspection) is of order a minute, however, only moderate persistence is required to obtain a subset of adequate results. For fainter objects or fainter parts of the spectrum, many short (and therefore unsmeared) exposures can be stacked computationally—public-domain software exists to perform this stacking, which is straightforward providing the total time-span occupied by the exposures is not so large that significant field-rotation occurs, although that too can be corrected computationally. It may also be noted that in addition to the more familiar IRAF packages, easy-to-use public-domain software specifically designed for the reduction of CCD spectra in a Windows environment is also available—see, e.g. the Visual Spec (VSPEC) software package at http://valerie.desnoux.free.fr/vspec/.

Note that the solar spectrum, convolved with Uranus' albedo and the responsivity of this CCD detector, are such that there is no need for order-separation filters, provided the wavelength range studied extends to less than 700 nm, since typical CCD sensitivities only become significant above 350 nm. It may be noted that the (blazed) Rainbow Optics grating used here puts 10% or less of the light into the second order.

Although more sophisticated wavelength calibrations can be applied, the spectrum shown in Fig. 2 was obtained simply by relating wavelength by a polynomial (in this instance, two terms only—a linear function) and adjusting the polynomial terms by trial and error until the best match with the published spectrum was found. The responsivity of the CCD was corrected for by similarly analyzing a spectrum of Vega (admittedly at a rather higher airmass) which

Table 1
Observing sites and equipment

Observer	Site	Equipment
West	Mulvane, KS, USA 37°28′N 97°15′W altitude 300 m	0.2 m SCT (Meade LX200) at f/6.3 SBIG ST-8 CCD as slitless non-objective spectrograph using Rainbow Optics 200 grooves/mm blazed transmission grating and Murnaghan I,V filters
Lorenz	Tucson AZ, USA 32°12′N 111°54′W altitude 700 m	0.2 m SCT (Meade LX200) at f/10 Starlight Express MX516 CCD as slitless spectrograph using Rainbow Optics 200 grooves/mm blazed transmission grating
Dooley	Tucson AZ, USA 32°11′N 111°54′W altitude 700 m	0.53 m Cassegrain at f/5.6 Starlight Express MX516 CCD with Coherent Optics narrowband filters
Fujii	Okayama, Japan 34°40′N 133°32′E altitude 400 m	0.28 m SCT (Celestron C11) at f/10 SBIG ST-6 CCD coupled to homebuilt spectrograph using Bausch & Lomb 600 grooves/mm reflectance grating 0.1 mm slit on Al coated glass 150 mm focal length 25 mm diameter collimator mirror 50 mm Canon camera lens (f/1.4)

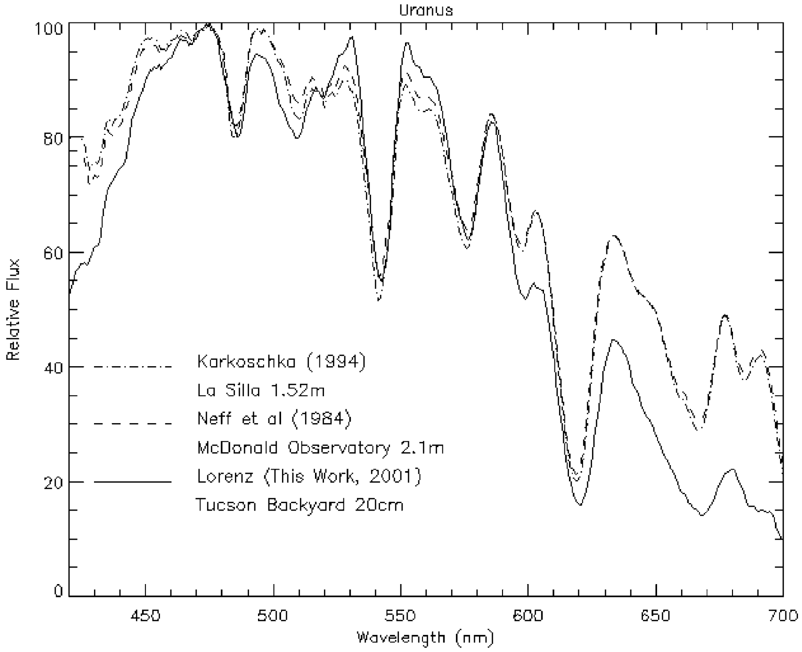

Fig. 3. Spectrum of Uranus obtained in Tucson on 17th September 2001 by a 1 min exposure using an 8-in telescope. Published spectra have been degraded to the corresponding ~ 4 nm spectral resolution. The deviation from the published results longward of 570 nm is probably due to airmass differences between the flux calibration star (Vega) and the target.

may account for some of the flux difference at longer wavelengths.

The spectral resolution that is obtained is limited to several nm, both by the depth of focus of the diffracted light, and by the angular size of the object: focal reducers may help in minimizing the angular size of the zeroth-order image, and thus the smear of the spectrum.

3. Spectroscopy of Neptune

Fig. 4 shows a similar spectrum of Neptune. Neptune being fainter requires longer exposures—that shown used a sum of 4 separate 1-min exposures. Again the agreement with published spectra (degraded to our spectral resolution) is excellent. There appears to be some darkening longward

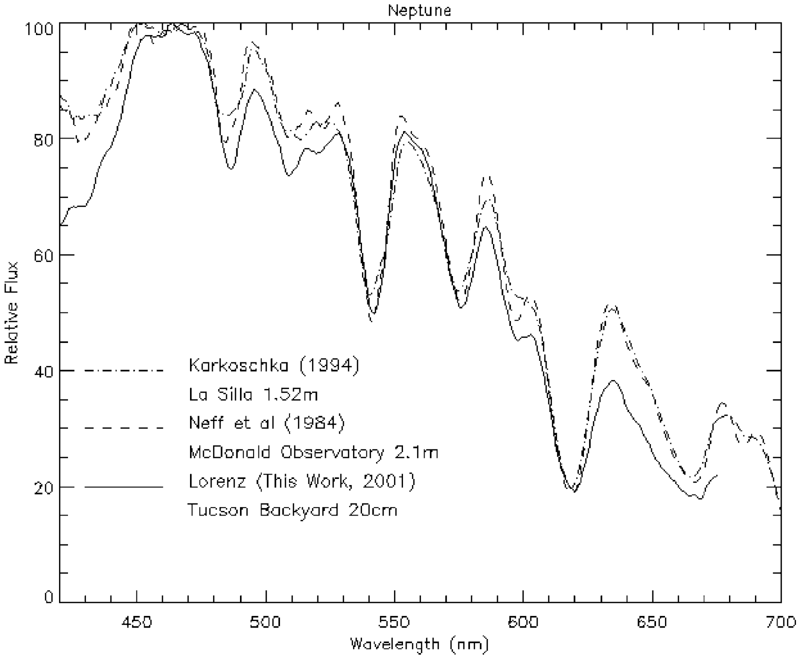

Fig. 4. Spectrum of Neptune obtained in Tucson on 23rd September 2001 by summing four 1-min exposures using an 8-in telescope. Published spectra have been degraded to the corresponding ~ 4 nm spectral resolution. The deviation from the published results around 640 nm again is probably due to airmass differences in flux calibration.

of 570 nm—although this is consistent with the trend observed by Karkoschka (1998) between 1993 and 1995 it seems a little strong, and a likely explanation is that the flux calibration star Vega was at a lower airmass than Neptune. This exercise is intended as a proof-of-concept only, however, and it is clear that even this simple equipment can obtain useful results: with more careful use of calibration stars seasonal and possibly cloud-related changes may be monitored.

4. Spectroscopy of Titan

Fig. 5 shows a spectrum of Titan obtained with a small telescope and a 1 min exposure. Note that the CCD camera used in this case was an SBIG ST-8; this camera has a better near-infrared response than the Starlight Express unit used for Uranus and Neptune, and thus the wavelength range shown is slightly redder.

To obtain the Titan spectrum from the image, scattered light from Saturn had to be removed by interpolation (i.e. subtracting the mean of the rows of pixels above and below those containing the Titan spectrum). This background amounts typically to a significant fraction of the Titan signal (one quarter at the peak Titan wavelength): although it is not difficult to find the Titan signal and remove the background such that the spectrum is recognizably that of Titan, quantitative interpretation will require that the scattered light problem be tackled with extreme care.

Rather better results can be obtained with conventional slit spectrometers. An example is the unit by SBIG, which sells for around $4000. One of us (Fujii) has built a similar instrument and the resultant spectrum, of Titan with a resolution of about 1 nm is given in Tables 2 and 3 and shown in Figs. 6 and 7. Other details and spectra can be inspected at http://www1.harenet.ne.jp/~aikow/. Flux calibration was performed by observing the 4th magnitude standard HR 1544 which was at the same (within 1° or 2°) airmass as Titan—the calibration spectrum was downloaded from the website of the European Southern Observatory. Wavelength calibration was performed using a neon lamp.

Both the darkening towards the blue and a feature at around 550 nm may be a real seasonal change, associated with the methane band at that wavelength. Some weak brightening relative to previously published spectra may also be apparent in the 619 nm methane band, detail of which is shown in Fig. 6 where the reproducibility of the observations (and equivalently, the apparent short-term nonvariability of Titan) is evident from the agreement of several nights' spectra taken over a period spanning three months.

5. Photometry of Titan

In an attempt to measure a lightcurve for Titan and possibly search for cloud activity, we also performed photometry on Titan in December 2000 to March 2001.

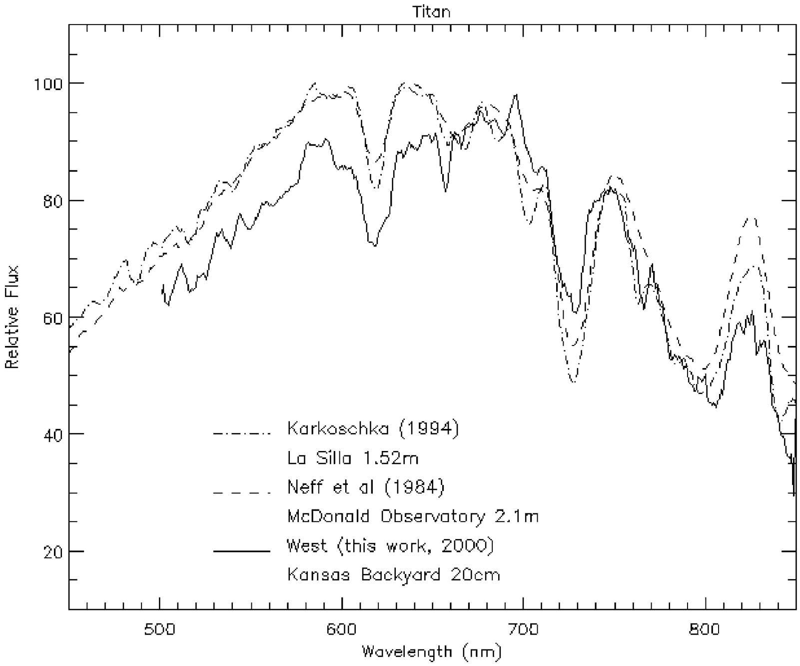

Fig. 5. Spectrum of Titan obtained on 16th December 2000 from a 1-min exposure with an 8-in telescope. Darkening at visible wavelengths is consistent with trend observed 1993–1995 by Karkoschka. The poorer quality of this spectrum is apparent—Titan would clearly benefit from longer exposures—but it is recognizably Titan.

Johnson V and Kron-Cousins I-band measurements were taken. (Kron-Cousins filters are designed to match magnitudes established with these filters and CCD detectors with photographic magnitudes taken with the widely-used Johnson filter system, compensating for the different spectral responsivities of the detectors.) The I-band filter has a full-width at half-maximum of 150 nm, centered around 800 nm, and the V-band is 90 nm wide, centered at 550 nm. It may be noted that this is one of the largest photometric datasets ever published on Titan (see Andersson, 1977).

It was hoped that a longitudinal lightcurve would be detectable with the I-filter, since this filter probes the methane window at around 830 nm, and that this lightcurve would have an order of 5% (based on the strength of the lightcurve at 940 nm). This corresponds to a variation of 0.05–0.10 magnitudes.

The observed magnitudes were reduced to a normalized form (i.e. the corresponding zero-phase angle magnitude at 1 AU from the sun, 1 AU from the Earth) by the formula

$$I(1,0) = I_o + 5\log_{10}(r\Delta) - k\alpha,$$

where r is the distance from the sun in AU, Δ the distance from Earth and α the phase angle at the time the observed magnitude I_o was recorded. k is a phase coefficient (0.055 magnitudes/deg for V-band, 0.001 magnitudes/deg for I-band: this empirical coefficient—see, e.g. Lockwood et al., 1986—takes into account both the phase angle dependence of Titan's surface brightness, as well as the purely geometric dependence of total brightness due to the illuminated area fraction). Details of the calibration stars used are available on request—the data themselves are given in Table 1.

Fig. 8 shows the results—a variation of rather larger than expected amplitude was found, and not of the expected pattern. While the short-wavelength window we are probing would be sensitive to cloud effects, it seems that ascribing such a cause is not justified. It is notable that the extreme brightness values are apparent near longitudes 0 and 180, in other words when Titan is closest to Saturn as seen in the sky. Photometric observations by Schmude et al. (1993), also with a small telescope, show strong scattered light in the vicinity of Titan, varying by about half-to-one magnitude per ring diameter—see also Gennet and Binzel (1983). Thus small errors in background subtraction can lead to significant errors in the photometry of Titan.

The challenges of the lightcurve notwithstanding, the average magnitudes obtained are likely to be more robust, since they only depend on absolute (rather than longitude-relative) background subtraction error. The average values obtained are $V(1,0) = -1.29 \pm 0.08$ and $I(I,0) = -2.03 \pm 0.06$. The V magnitude of Titan corresponds closely to the Strongren y-magnitude recorded by Lockwood et al. over the years (see, e.g. Lorenz et al., 1999), and our data point seems to fall on the expected curve.

We also performed narrowband CCD photometry using the University of Arizona campus 21″ telescope and narrowband filters. The filters were chosen to be centered on a methane band and a window, at 790 and 750 nm,

Table 2
Titan spectrum obtained in Okayama around 20.00 h UT on October 19, 2001 under very clear sky conditions. Wavelength λ in Å (0.1 nm) and flux F in units of 10^{-14} erg/cm^2/s/Å

λ	F	λ	F	λ	F	λ	F	λ	F	λ	F
4427	102	4894	149	5361	190	5828	213	6295	211	6762	212
4434	106	4901	152	5368	182	5835	211	6302	210	6769	210
4442	104	4909	149	5376	186	5843	213	6310	211	6777	211
4449	101	4916	142	5383	189	5850	212	6317	210	6784	211
4456	107	4923	146	5390	187	5857	206	6324	214	6791	209
4464	111	4931	150	5398	178	5864	209	6331	216	6798	205
4471	112	4938	151	5405	177	5872	213	6339	213	6806	204
4478	112	4945	156	5412	181	5879	212	6346	215	6813	202
4485	113	4952	152	5419	185	5886	198	6353	216	6820	199
4493	118	4960	152	5427	184	5894	190	6361	215	6828	199
4500	122	4967	156	5434	184	5901	203	6368	217	6835	197
4507	119	4974	153	5441	191	5908	211	6375	219	6842	195
4515	115	4982	149	5449	193	5916	210	6383	218	6849	198
4522	109	4989	153	5456	195	5923	210	6390	215	6857	197
4529	114	4996	153	5463	197	5930	210	6397	213	6864	181
4537	117	5004	147	5470	198	5937	210	6404	211	6871	147
4544	116	5011	144	5478	195	5945	208	6412	210	6879	166
4551	120	5018	146	5485	199	5952	207	6419	211	6886	178
4558	122	5025	152	5492	204	5959	210	6426	211	6893	174
4566	123	5033	153	5500	203	5967	209	6434	211	6901	180
4573	122	5040	149	5507	201	5974	209	6441	214	6908	186
4580	120	5047	151	5514	202	5981	207	6448	213	6915	190
4588	121	5055	158	5522	204	5989	209	6455	211	6922	193
4595	122	5062	158	5529	200	5996	211	6463	210	6930	194
4602	125	5069	155	5536	202	6003	209	6470	210	6937	195
4610	128	5076	151	5543	204	6010	209	6477	210	6944	192
4617	129	5084	154	5551	205	6018	207	6485	208	6952	191
4624	129	5091	158	5558	202	6025	207	6492	202	6959	188
4631	126	5098	156	5565	198	6032	214	6499	203	6966	189
4639	124	5106	155	5573	198	6040	216	6507	210	6974	185
4646	124	5113	161	5580	198	6047	214	6514	207	6981	181
4653	127	5120	158	5587	192	6054	214	6521	206	6988	178
4661	124	5128	155	5595	194	6061	214	6528	208	6995	172
4668	124	5135	154	5602	196	6069	214	6536	207	7003	164
4675	128	5142	153	5609	202	6076	212	6543	205	7010	165
4682	130	5149	156	5616	198	6083	209	6550	197	7017	160
4690	129	5157	159	5624	199	6091	209	6558	173	7025	159
4697	126	5164	143	5631	201	6098	207	6565	165	7032	162
4704	127	5171	137	5638	198	6105	206	6572	190	7039	163
4712	134	5179	145	5646	200	6113	207	6580	198	7046	166
4719	137	5186	148	5653	199	6120	200	6587	197	7054	169
4726	134	5193	155	5660	195	6127	197	6594	195	7061	171
4734	137	5201	161	5667	199	6134	191	6601	198	7068	173
4741	140	5208	161	5675	203	6142	189	6609	200	7076	176
4748	140	5215	166	5682	198	6149	190	6616	198	7083	176
4755	137	5222	164	5689	197	6156	184	6623	195	7090	176
4763	138	5230	163	5697	199	6164	179	6631	194	7098	177
4770	144	5237	171	5704	194	6171	179	6638	194	7105	182
4777	145	5244	175	5711	192	6178	181	6645	196	7112	183
4785	144	5252	175	5719	200	6186	179	6652	195	7119	182
4792	146	5259	171	5726	204	6193	178	6660	191	7127	182
4799	146	5266	157	5733	203	6200	180	6667	189	7134	183
4807	146	5273	163	5740	202	6207	183	6674	190	7141	181
4814	150	5281	174	5748	199	6215	182	6682	190	7149	177
4821	148	5288	182	5755	197	6222	185	6689	192	7156	173
4828	147	5295	180	5762	199	6229	189	6696	194		
4836	147	5303	183	5770	201	6237	194	6704	196		
4843	146	5310	188	5777	199	6244	198	6711	197		
4850	136	5317	186	5784	198	6251	199	6718	198		
4858	121	5325	176	5792	201	6258	205	6725	202		
4865	126	5332	179	5799	205	6266	212	6733	205		
4872	140	5339	183	5806	206	6273	210	6740	206		
4879	143	5346	185	5813	209	6280	208	6747	208		
4887	141	5354	191	5821	213	6288	212	6755	210		

Table 3
Instrumental photometric magnitudes for Titan

Calendar date	Time (CST)	Band, mag,	Comparison stars	Note
12/4/00	18:47	V, 8.06	TYC 1239 553, TYC 1239 753 1	7
12/16/00	18:24	V, 8.067	TYC 1238 1126 1, TYC 1238 1120 1, TYC 1234 705 1	3
12/21/00	18:20	V, 8.198	HIP 16538, HIP 16469, TYC 1234 705 1[a]; HIP 16598	1
12/21/00	18:32	I, 7.38	HIP 16538, HIP 16469	1
12/22/00	18:58	V, 8.151	HIP 16538, HIP 16469, TYC 1234 705 1[a]	1
12/22/00	19:23	I, 7.315	HIP 16469, HIP 16538	1
12/29/00	19:51	V, 8.195	HIP 16469	2, 4
12/29/00	20:48	I, 7.276	HIP 16469	2, 4
1/3/01	21:14	V, 8.176	HIP 16268	1
1/3/01	20:42	I, 7.472	HIP 16268	1
1/4/01	21:14	V, 8.124	HIP 16268	1
1/4/01	20:43	I, 7.358	HIP 16268	1
1/5/01	19:34	V, 8.202	HIP 16268	3
1/14/01	20:06	V, 8.103	HIP 16268, TYC 1234 288 1	1, 2
1/14/01	20:28	I, 7.418	HIP 16268, TYC 1234 288 1	1, 2
1/17/01	20:17	V, 8.153	HIP 16268, TYC 1234 288 1, HIP 16117	1
1/17/01	19:56	I, 7.425	HIP 16268, TYC 1234 288 1	1
1/18/01	20:17	V, 8.141	HIP 16268, TYC 1234 288 1, HIP 16117	1
1/18/01	19:56	I, 7.466	HIP 16268, TYC 1234 288 1, HIP 16117	1
1/19/01	20:49	V, 8.199	HIP 16268, TYC 1234 288 1, HIP 16117	1
1/19/01	21:02	I, 7.490	HIP 16268, TYC 1234 288 1, HIP 16117	1
1/22/01	19:07	V, 8.011	HIP 16268, TYC 1234 288 1, HIP 16117	1, 2
1/22/01	18:42	I, 7.378	HIP 16268, TYC 1234 288 1, HIP 16117	1, 2
1/24/01	20:15	V, 8.200	HIP 16268, TYC 1234 288 1, HIP 16117	1
1/24/01	18:42	I, 7.489	HIP 16268, TYC 1234 288 1, HIP 16117	1
1/26/01	21:44	V, 8.149	HIP 16268, TYC 1234 288 1	1
1/26/01	21:20	I, 7.410	HIP 16268, TYC 1234 288 1	1
1/29/01	21:29	V, 8.225	HIP 16268, TYC 1234 288 1	1
1/29/01	21:23	I, 7.471	HIP 16268, TYC 1234 288 1	1
1/31/01	21:21	V, 8.28	HIP 16268, TYC 1234 288 1	10
1/31/01	21:31	I, 7.506	HIP 16268, TYC 1234 288 1	10
2/01/01	19:16	V, 8.225	HIP 16268, TYC 1234 288 1, HIP 16117	1
2/01/01	19:10	I, 7.504	HIP 16268, TYC 1234 288 1, HIP 16117	1
2/03/01	19:56	V, 8.229	HIP 16268, TYC 1234 288 1, HIP 16152	1
2/03/01	19:45	I, 7.481	HIP 16268, HIP 16152	1
2/04/01	20:39	V, 8.209	HIP 16268, TYC 1234 288 1	1
2/04/01	20:34	I, 7.525	HIP 16268, TYC 1234 288 1	1
2/09/01	18:54	V, 8.248	HIP 16268, TYC 1234 288 1	1
2/09/01	19:09	I, 7.501	HIP 16268, TYC 1234 288 1	1
2/10/01	19:30	V, 8.275	HIP 16268, TYC 1234 288 1	1
2/10/01	19:25	I, 7.528	HIP 16268, TYC 1234 288 1	1
2/11/01	19:27	V, 8.292	HIP 16268	1
2/11/01	19:00	I, 7.560	HIP 16268	1
2/15/01	19:24	V, 8.292	HIP 16268	5
2/15/01	19:00	I, 7.729	HIP 16268	5
2/16/01	19:08	V, 8.309	TYC 1238 68 1[a], TYC 1238 141 1, TYC 1238 66 1, TYC 1238 25 1	9
2/16/01	19:15	I, 7.557	TYC 1238 68 1[a], TYC 1238 141 1, TYC 1238 66 1, TYC 1238 25 1	6
2/17/01	21:09	V, 8.345	TYC 1238 68 1[a], TYC 1238 141 1, TYC 1238 66 1, TYC 1238 25 1[a], HIP 16469[a]	6
2/17/01	21:14	I, 7.712	TYC 1238 68 1[a], TYC 1238 141 1, TYC 1238 66 1, TYC 1238 25 1	10
2/18/01	19:54	V, 8.370	TYC 1238 68 1, TYC 1238 141 1, TYC 1238 66 1, TYC 1238 25 1	9
2/18/01	20:09	I, 7.664	TYC 1238 68 1, TYC 1238 141 1, TYC 1238 66 1, TYC 1238 25 1	9
2/19/01	19:28	V, 8.391	TYC 1238 68 1, TYC 1238 141 1, TYC 1238 66 1[a],TYC 1238 25 1[a]	9
2/19/01	19:40	I, 7.603	TYC 1238 68 1, TYC 1238 141 1, TYC 1238 66 1, TYC 1238 25 1	9
2/22/01	19:39	V, 8.078	HIP 16538	2, 11
2/22/01	19:51	I, 7.266	HIP 16538	2, 11
2/25/01	20:03	V, 8.419	HIP 16598, TYC 1238 550 1, HIP 16512	1
2/25/01	20:24	I, 7.670	HIP 16598, HIP 16512	1
3/3/01	19:51	V, 8.424	TYC 1234 705 1, TYC 1238 1126 1, HIP 16598, TYC 1238 550 1	10
3/3/01	19:28	I, 7.604	TYC 1234 705 1, HIP 16598, TYC 1238 550 1	10
3/4/01	20:26	V, 8.400	HIP 16641, HIP 16598, TCY 1238 1126 1, TYC 1234 705 1	10
3/4/01	20:14	I, 7.668	HIP 16469, HIP 16598, TYC 1234 705 1	10
3/5/01	19:49	V, 8.436	HIP 16641, TYC 1238 1126 1, HIP 16598	10

Table 3 (*continued*)

Calendar date	Time (CST)	Band, mag,	Comparison stars	Note
3/5/01	19:30	I, 7.677	HIP 16641, HIP 16598	10
3/12/01	20:02	V, 8.346	HIP 16802, TYC 1239 9201 1	1
3/12/01	19:57	I, 7.618	HIP 16802	1
3/13/01	19:22	V, 8.362	TYC 1239 920 1, TYC 1239 1016 1, TYC 1239 553 1, TYC 1239 753 1	3
3/17/01	19:52	V, 8.486	HIP 16983, TYC 1239 998 1, TYC 1239 147 1, TYC 1239 629 1	10, 11
3/17/01	19:38	I, 7.707	HIP 16983	10, 11

[a] Given a photometric weight of 0.5 in MIRA software due to residual > 0.1.

Notes: 1. Average magnitude from measurement of two images per band. 2. Titan was very close to Saturn, Saturn's glare affected photometry. 3. Two V band measurements, no I band measurements. 4. Two V band measurements, one I band measurement. 5. Clouds resulted in lower s/n. Three of four observations had $s/n < 100$. 6. Observation is average from measurements of two different fields (different comparison stars). 7. One measurement in V band only. 8. Larger dispersion in measurements than normal. 9. Average of three observations in that band, average weighted by the number of reference stars used in individual observations. 10. Based on four observations per band, average weighted by the number of reference stars used to derive the magnitude. 11. Cloud cover resulted in some measurements with $s/n < 100$.

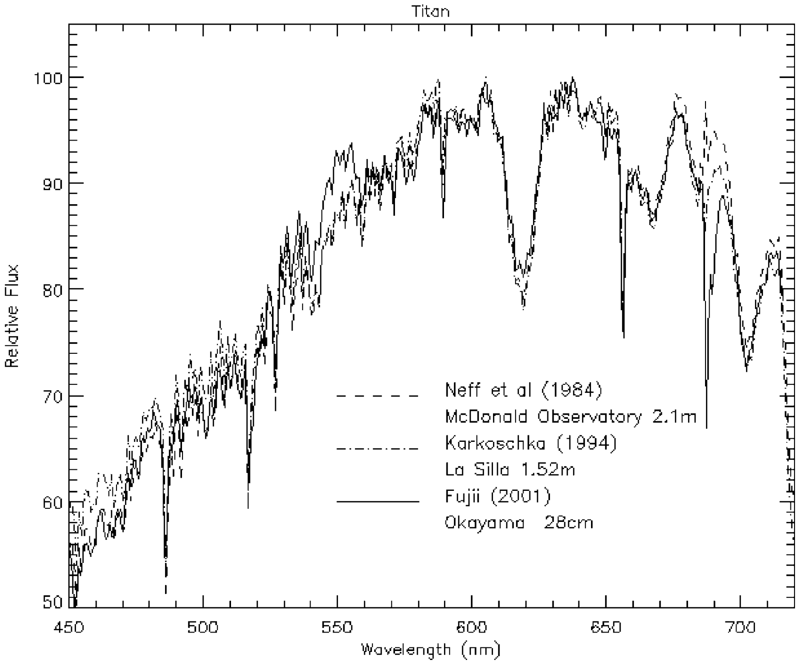

Fig. 6. Spectrum of Titan obtained by Mitsugu Fujii from an urban Japanese site on 10 October 2001. Flux calibration was performed against star HR1544 (Pi2 Orionis), which was at the same altitude (59–60°) during the observations as Titan, combining 4 exposures totalling 26 min. The observation used a homebuilt spectrograph with a 0.1 mm (7 arc s) slit, and hence permits much higher spectral resolution than the previous (slitless) spectra reported in this paper. The agreement with published data is excellent. Slight darkening below 520 nm is probably a real seasonal change, as may be the apparent depth of the 619 nm methane band. Bright feature at 550 nm is not yet explained.

respectively. These wavelengths (suggested to us by Bouchez, pers. commun., 2001, Roe, pers. commun., 2001) are short enough in wavelength that our CCD has reasonable sensitivity, and the 750 nm window is free of significant terrestrial water absorption (unlike the better known 940 nm window). The filters we used were obtained from Coherent Optics Inc. (part numbers 35-4266 and 35-4365, with measured central wavelengths of 753.4 and 792.7 nm, respectively, and FWHM bandpass of 11.2 and 10.6 nm). The bandpasses, together with those of the standard *V*, *I* and *R* filters, are shown in Fig. 9. The filters we used lack antireflection coatings, which may have exacerbated the scattered light problem and in our initial observing run. Although (Fig. 10) we would expect a ~ 2% lightcurve, the scatter in our data was too large to discern the surface lightcurve (and indeed was similar in both the 750 and 790 nm filters).

Averaging the narrowband observations (10 nights) yields normalized (opposition) fluxes of $1.43 \pm 0.26 \times 10^{-12}$ erg/s/cm^2/A (one sigma) for the 750 nm filter and $0.74 \pm 0.14 \times 10^{-12}$ erg/s/cm^2/A (one sigma) for the 790 nm filter. With these errors, the 750 nm flux is in agreement with the values ($\sim 1.67 \times 10^{-12}$ erg/s/cm^2/A) reported by Lockwood et al. (1986), but the 790 nm flux

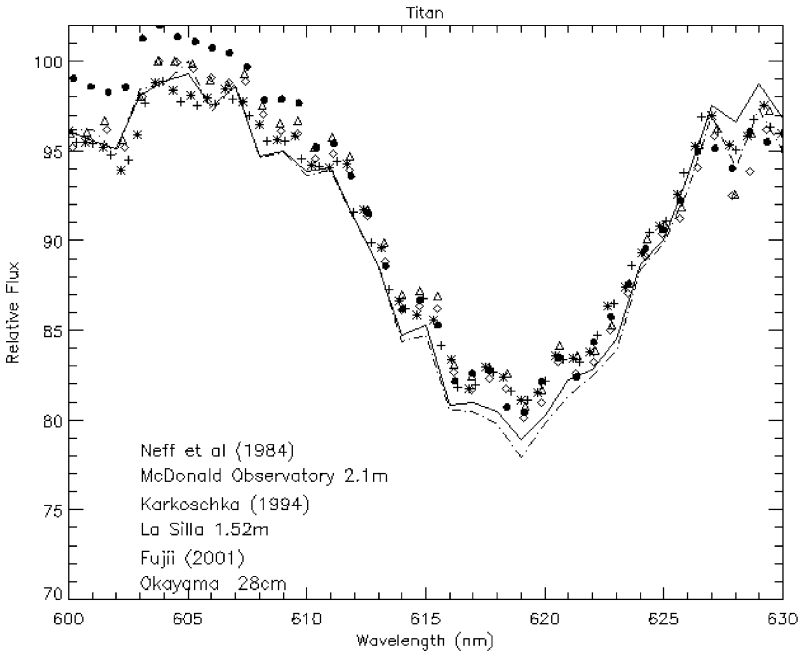

Fig. 7. Detail of the 619 nm methane band in Titan's spectrum. The symbols represent observations by Fujii on October 10th and 19th, December 2001, and 2nd and 6th January 2002. Narrowing and shallowing of the band would be expected were clouds to be present in the upper troposphere: no evidence for cloud variations at a ∼ 10% level are seen. The band appears to by slightly (1–2%) shallower in 2001 than in the previous observations—perhaps symptomatic of the southern polar opacity observed in the lower atmosphere by Lorenz et al. (2001) and Roe et al. (2002).

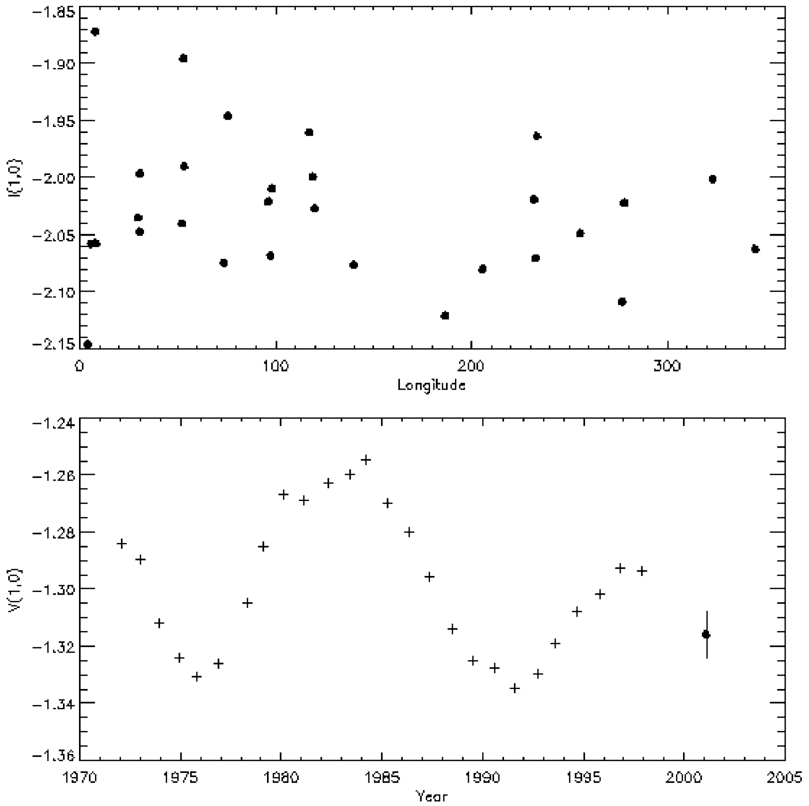

Fig. 8. Photometry using amateur equipment. Top panel is a set of I-band observations over 3 months by West in late 2000/early 2001 plotted against orbital longitude. The well-known lightcurve peaking around longitude 110 is not seen. The lower panel is the average of the corresponding V-band observations (solid circle with 1-sigma error bar) compared with y-photometry by Lockwood over the last 30 years—the backyard result seems quite reasonable.

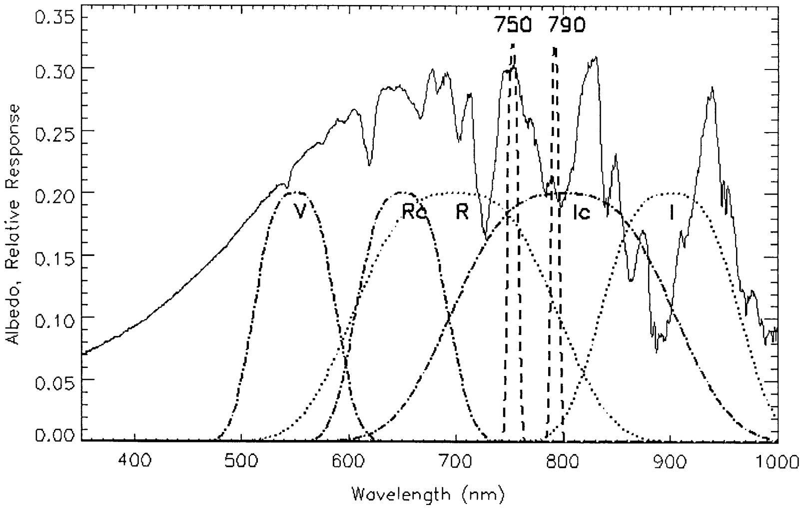

Fig. 9. Titan albedo spectrum from Karkoschka (1995) with filter bandpasses superimposed. Note that the Kron–Cousins filters (Rc, Ic- dot-dash line) have substantially different bandpasses from the Johnson filters (R, I) shown with dotted lines; V bandpasses are the same for both filter systems, but do not sample a particularly interesting part of Titan's spectrum. The effective wavelengths sensed will be modified by the shape of the solar spectrum (biasing R and I towards shorter wavelengths) and the spectral sensitivity of the detector used. The narrowband filters used in this work at 750 and 790 nm are shown with dashed lines.

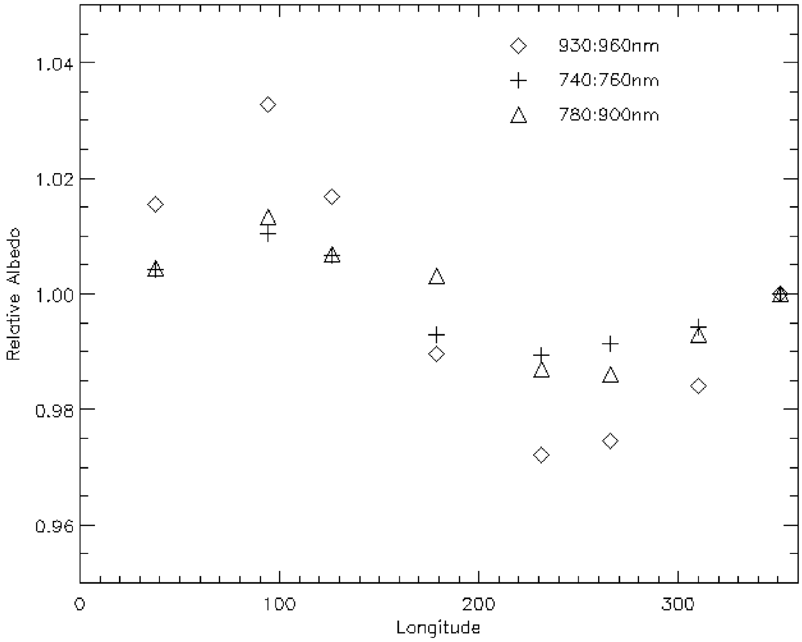

Fig. 10. Titan's lightcurve measured from a set of disk-integrated spectra recorded with the Space Telescope Imaging Spectrograph in 2000 (PI Young, see e.g. Lorenz et al., 2001). Symbols show normalized Titan flux averaged unweighted over the wavelength ranges shown (i.e. the albedo curve is weighted by the solar flux, but not by any assumed instrument responsivity.) The 940 nm window shows a ~ 9% lightcurve, but this wavelength region is significantly affected by water vapor absorption and the responsivity of many amateur CCDs decline at this long wavelength. The broad 780–900 nm wavelength (simulating approximately the Johnson I-band filter) shows approximately a 2% lightcurve, as does a narrowband region centered on 750 nm, which is unaffected by water vapor.

appears to be lower at the two-sigma level: Lockwood gives $\sim 1.0 \times 10^{-12}$ erg/s/cm^2/A. The drop in methane-band flux would be consistent with a reduction in the high-altitude haze over Titan's southern hemisphere which is presently exposed to the Earth (see Lorenz et al., 2001).

6. Conclusions

We have shown that small telescopes and relatively inexpensive instrumentation can make useful contributions in the study of the outer planets and Titan. This equipment, and the manpower required to take and reduce the observations, are well within the capabilities of most colleges and amateur astronomers. Observed spectra agree well with published results, and some seasonal change—consistent with previously observed trends—can be detected.

Titan is a particularly attractive object to study spectroscopically in coming years. Not only will interest be particularly high owing to the imminent arrival of the Cassini–Huygens mission, but there is a progression of novelty in studying it which encourages both amateurs and astronomy students to pursue its study further. A first spectrum shows clearly how Titan is very different from the Galileans, reproducing Kuiper's 1944 discovery. More patient monitoring over a few weeks should bring out Titan's near-infrared lightcurve, reproducing work by Lemmon, Coustenis, Noll, Griffith and others of 1992–1995 (although technologically this discovery could have been made some 20 years earlier!). It remains to be seen whether small-telescope observations can repeat and extend upon—more particularly in a believable manner with a realistic and accurate discussion of uncertainties—the detection of clouds on Titan. Successful observers are urged to contact the first author and to publish their observations via the BAA, ALPO or through the referred literature. Although slitless observations are of pedagogical interest and with care might show seasonal changes, the accuracy required for robust detection of clouds may present too great a challenge to small-aperture telescopes. Although our attempts at CCD photometry have met with only limited success, more experienced observers and especially careful removal of scattered Saturn light can likely do better. Conventional (slit) spectrometers seem to offer most promise for believable and robust results for Titan.

Another similar project of probable interest and usefulness would be monitoring of Io for volcanic activity—Io occasionally shows dramatic brightening in the near-infrared as short as 1 μm. As for Titan's surface and cloud contrasts, these events are also much more easily detected at longer wavelengths than those accessible to simple CCD cameras. A technological development that would considerably enhance small-telescope observers in these areas (since surface contrasts become 10–20% rather than only a few, and contrasts associated with clouds may be even larger—see Griffith et al., 1998) would be low-cost and sensitive cameras able to operate in the 1–2 μm range. An amateur infrared photometer for use in the J- and H-bands has also recently been developed (G. Persha, pers. commun., see www.optecinc.com) although scattered Saturn light presents severe difficulties to aperture photometry of Titan (see e.g. Schmude, 1993).

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References

Andersson, L.F., 1977. Variability of Titan—1896–1974. In: Burns, J.A. (Ed.), Planetary Satellites. University of Arizona Press, Tucson, pp. 451–459.

Coustenis, A.C., Lellouch, E., Maillard, J-P., McKay, C.P., 1995. Titan's surface: composition and variability from near-infrared Albedo. Icarus 118, 87–104.

Cruikshank, D.P., Morgan, J.S., 1980. Titan: suspected near-infrared variability. Astrophys. J. 235, L53–L54.

Gavin, M., 2000. Backyard spectroscopy. Sky Telescope 57–62.

Gennet, R., Binzel, R., 1983. Solar System Photometry Handbook. Willmann-Bell, Richmond, VA.

Glumac, N., Sivo, J., 1999. Building a fiber-optic spectrograph. Sky Telescope 134–139.

Griffith, C.A., 1995. Evidence for surface heterogeneity on Titan. Nature 364, 511–514.

Griffith, C.A., Owen, T., Wagener, R., 1991. Titan's surface and troposphere, investigated with ground-based, near-infrared observations. Icarus 93, 362–378.

Griffith, C.A., Owen, T., Miller, G.A., Geballe, T., 1998. Transient clouds in Titan's lower atmosphere. Nature 395, 575–578.

Griffith, C.A., Hall, J.L., Geballe, T., 2000. Detection of daily clouds on Titan. Science 290, 509.

Kannappan, S., Fabricant, D., 2000. Getting the most from a CCD spectrograph. Sky Telescope 125–132.

Karkoschka, E., 1995. Spectrophotometry of the Jovian planets and Titan at 300- to 1000-nm wavelength: the methane spectrum. Icarus 111, 174–192.

Karkoschka, E., 1998. Methane, ammonia, and temperature measurements of the Jovian planets and Titan from CCD-spectrophotometry. Icarus 133, 134–146.

Lemmon, M.T., Karkoschka, E., Tomasko, M., 1993. Titan's rotation: surface feature observed. Icarus 103, 329–332.

Lemmon, M.T., Karkoschka, E., Tomasko, M., 1995. Titan's rotational light-curve. Icarus 113, 27–38.

Lockwood, G.W., Thompson, D.T., 1999. Photometric variability of Uranus, 1972–1996. Icarus 137, 2–12.

Lockwood, G.W., Lutz, B.L., Thompson, D.T., Bus, E.S., 1986. The albedo of Titan. Astrophys. J. 303, 511–530.

Lorenz, R.D., Smith, P.H., Lemmon, M.T., Karkoschka, E., Lockwood, G.W., Caldwell, J., 1997. Titan's north–south asymmetry from HST and Voyager imaging: comparisons with models and groundbased photometry. Icarus 127, 173–189.

Lorenz, R.D., Lemmon, M.T., Smith, P.H., Lockwood, G.W., 1999. Seasonal change on Titan observed with the hubble space telescope WFPC-2. Icarus 142, 391–401.

Lorenz, R.D., Young, E.F., Lemmon, M.T., 2001. Titan's smile and collar: HST observations of seasonal change 1994–2000. Geophys. Res. Lett. 28, 4453–4456.

Mais, D., 2002. Amateur astronomical spectroscopy. Astronomy Now 16 (3), 52–54.

McCord, T., Johnson, T.V., Elias, J.H., 1971. Saturn and its satellites: narrowband spectrophotometry (0.3–1.1 mm). Astrophys. J. 165, 413–424.

Neff, J.S., Humm, D.C., Bergstrahl, J.T., Cochran, A.L., Cochran, W.D., Barker, E.S., Tull, R.G., 1984. Absolute spectrophotometry of Titan, Uranus and Neptune 3500–10, 500 Å. Icarus 60, 221–235.

Noll, K., Knacke, R.F., 1993. Titan: 1–5 micron photometry and spectrophotometry and a search for variability. Icarus 101, 272–281.

Roe, H.G., de Pater, I., Macintosh, B.A., Gibbard, S., Max, C.E., Mckay, C.P., 2002. Titan's atmosphere in late southern spring observed with adaptive optics on the W.M. Keck II 10-Meter Telescope. Icarus 157, 254–258.

Schmude Jr., R.W., Bruton, D., 1993. Wideband photometry of Titan in 1992. IAPPP Commun. 51, 37–40.

West, J.D., Alexander, D.R., 2001. Design of a low-resolution non-objective slitless spectrograph. Astron. Society of the Pacific, submitted for publication.