INTRODUCTION

Sleep and circadian rhythm systems are fundamental regulatory processes of the nervous system, and the most ubiquitous endogenous controls of human biobehavioral functions—everyone is internally programmed to sleep every night. The need for sleep is a homeostatic drive that occurs regardless of time of day, but it is also modulated by the endogenous circadian pacemaker. Conversely, the endogenous circadian pacemaker oscillates regardless of the need for sleep, although its promotion of wakefulness can be overwhelmed by elevated homeostatic sleep drive. These two powerful neurobiological systems interact continuously to control brain state (i.e., waking vs. sleep) and the intensity of state (e.g., alert vs. sleepy). Sleep and circadian rhythmicity also temporally modulate a wide range of physiological functions (e.g., body temperature, cardiovascular activity, respiration, immune responses), hormonal functions (e.g., growth hormone, melatonin, cortisol, thyroid hormones), behavioral functions (e.g., movement, posture, reaction time), and cognitive functions (e.g., fatigue, alertness, vigilance, memory, cognitive throughput).

No astronaut—no matter how much training, preparation, nutrition, psychosocial support, or environmental protection is provided—is immune from the daily control of physiology and performance by the homeostatic drive for sleep and the endogenous circadian timing system. Failure to take these two interactive neurobiological imperatives into account when planning human activities in space will have catastrophic consequences.

The need for sleep and the circadian pacemaker have a sustained influence over many biomedical systems essential for maintaining astronaut physical condition, mental health, and performance capability. Dysfunction of sleep and circadian systems can adversely affect an organism's ability to respond to environmental challenges and has been linked to physiological and psychological disorders. This area therefore has a high degree of relevance to a number of other space life science technical areas including research on muscle and bone loss, cardiovascular and immune changes, neurovestibular alterations and nutritional needs, and behavioral and psychological health in space flight.

SUMMARY OF PRESENTATIONS

The presentations in the Sleep and Chronobiology section fell broadly into a discussion on how much sleep is required in space, and if (as seems to be the case) astronauts fail to get enough sleep, what can be done about it? The overriding theme of these discussions is presented along with short summaries, written by the investigators themselves, describing their work which have been inserted at the appropriate position in the discussion.

Sleep in μG is disrupted
• Numerous studies have shown that on average, astronauts get only ~6 hours sleep per night (Monk)
  • Why is this?
  • How much sleep do we need?
  • What are the consequences?
  • What can we do about it?

From University of California San Diego, Division of Physiology, La Jolla, CA (K. Prisk) and university of California Davis, Section of Neurobiology, Physiology, and Behavior, Davis, CA (C. Fuller).
Why is sleep short in μG?
- No evidence for circadian disruption in short-duration (Shuttle) spaceflight (Monk)
- Limited evidence for a reduction in the circadian variation in body temperature in long-duration (Mir) spaceflight (Monk)
- Sleep disruption is NOT from respiratory factors (Prisk)
  - No change in ventilatory control
  - A reduction in sleep disturbances from respiratory causes

Sleep and Circadian Rhythms in Space: Short-Term Versus Long-Term Missions
T.H. Monk, D.J. Buysse, K.S. Kennedy and L.R. Rose
In a short duration mission with a stable work-rest schedule, we found stability and good entrainment in the subjects’ circadian rhythms, with baseline amplitude levels and no phase drift, although sleep durations were short and delta sleep was attenuated. In long duration missions, disturbed nights of sleep with durations less than 5h were associated with decrements in the following day’s self-rated performance. Also, there was evidence that after 100 days in space, circadian rhythms in oral temperature and subjective alertness became flattened, thus suggesting a diminished influence of the endogenous circadian pacemaker.

Sleep and Respiration in Microgravity
G.K. Prisk, A.R. Elliott, M. Paiva, and J.B. West
We hypothesized that part of the sleep disruption seen in space travelers may result from changes in the respiratory system, either in ventilatory control, or in upper airway patency as a result of the removal of gravity. Subjects studied during the Neurolab and STS-95 missions showed a decrease in hypoxic ventilatory response, similar to that seen in the supine position on the ground. Respiratory related arousals from sleep were virtually eliminated in spaceflight, and there was a large reduction in obstructive events during sleep, with a concomitant reduction in snoring. The results show that sleep disruption in spaceflight is not a result of respiratory causes, and that gravity plays a dominant role in the generation of obstructive sleep apnea on the ground.

How much sleep is enough?
- Habitually short sleepers are rare (Monk)
  - There are persons who sleep < 6 hours per night with no apparent decrement in performance
  - Such people are rare
    - <3% in a small, somewhat selected, study population
    - There is no evidence to suggest that “sleeping short” can be learned
- Can different sleep regimens compensate for a short night’s sleep? (Dinges)
  - Yes, for the most part
    - A nap during the day mostly accounts for a short night’s sleep
  BUT!
    - Total sleep period needs to be ~8.2 hours per day to avoid a cumulative performance deficit

A Sleep Diary and Questionnaire Study of Naturally Short Sleepers
Few diary and questionnaire measures showed reliable differences between naturally short sleepers and controls except the obvious ones related to sleep duration. There was some evidence for subclinical hypomanic symptoms in naturally short sleepers. The incidence of naturally short sleepers in an alumni sample was about 3% after shift work, daytime sleepiness, psychopathology and sleep disorders had been controlled.

Countermeasures to Neurobehavioral Deficits from Cumulative Partial Sleep Deprivation During Space Flight
D.F. Dinges, G. Maislin, H. Van Dongen, N.L. Rogers, M.P. Szuba, and J.M. Mullington,
This project is concerned with identifying ways to prevent neurobehavioral and physical deterioration due to inadequate sleep in astronauts during long-duration space flight. A ground-based experiment was completed on N = 91 healthy adult males and females. Cumulative neurobehavioral deficits across 10 days of chronic sleep restriction were used to develop response surface maps (RSMs) to determine the extent to
which (1) duration of sleep per 24 hr (range 4.2 hr – 8.2 hr); (2) the use of nocturnal anchor and diurnal nap sleeps; and (3) the placement of sleep within the circadian cycle, could mitigate cumulative impairments. The experiment showed that physiological sleep efficiency was high in all sleep restriction conditions—even those involving daytime naps as brief as 24 min—which suggests that the diverse range of restricted anchor + nap sleep durations tested in this protocol will likely result in sleep if used by astronauts. RSMs fit to neurobehavioral performance and alertness data revealed that the combination of a restricted duration anchor sleep and a diurnal nap help prevent the cumulative neurobehavioral deficits that can occur when only restricted anchor sleep is permitted in space flight.

What happens when we don’t get enough sleep?
- Subsequent daytime performance is impaired by shortened sleep (Van Dongen, Dinges)
  - The effect is cumulative
  - Most subjects need more than an 8 hour sleep period to avoid a performance decrement
  - There is a large inter-subject variability and performance loss may be predictable

Predicting Vulnerability to Performance Impairment from Sleep Loss
H.P.A. Van Dongen, D.F. Dinges and D.F. Neri
Astronauts obtain only ~6 hours sleep per night on average during space flight missions, which leads to a cumulatively enhanced probability of performance failure. This project investigates individual differences in vulnerability to performance impairment from sleep loss, quantifying the extent to which they reflect sleep-wake history and/or constitute a trait characteristic, and/or depend on prior experience with sleep deprivation. In addition, the project seeks to identify predictor variables for individuals’ variability to performance impairment from sleep loss for prospective evaluation and countermeasure targeting.

What can we do to ensure good sleep?
- Schedule adequate sleep time
- Ensure sleep occurs at the appropriate circadian phase
  - Exposure to bright light for several hours per day is effective but impractical
  - Several short (~15 minute) pulses of bright light totaling only ~30% of total exposure is nearly as effective (Czeisler)

Evaluation of Intermittent Bright Light Exposure as a Space Flight Countermeasure
C.A. Czeisler
Exposure to many hours of bright light during the early subjective night is known to shift the human circadian pacemaker to a later hour. We found that six brief (15 minute) exposures to bright light (10,000 lux) interspersed with hour-long gaps (< 1 lux) in the early subjective night elicits > 80% of the resetting effect of continuous exposure to bright light. These results have important implications for the use of brief pulses of bright light as a countermeasure to facilitate adaptation to phase shifts and non-24-hour day lengths required for space exploration. They also indicate that inadvertent exposure to brief episodes of bright light (such as occur in low earth orbit) may have a greater impact on circadian adaptation than previously recognized.

What about Mars?
- The Martian day is ~24.65 hours long
- Can we entrain the human circadian system to a day this long? (Wright)
  - With current light levels typical in spacecraft…NO.
  - With adequate (bright) light levels…MAYBE
- This problem may be even more acute in ground personnel supporting the mission

Circadian Entrainment, Sleep-Wake Regulation and Neurobehavioral Performance Under the Simulated Lighting Conditions of Spaceflight
K.P. Wright, Jr., R.E. Kronauer and C.A. Czeisler
Exploration class space missions require entrainment of the human circadian pacemaker in order to maintain a high level of cognitive performance and vigilance. This research effort is aimed at testing
whether the lighting conditions of spaceflight disturb circadian synchronization. Countermeasures will be required to maintain circadian entrainment of all astronauts during long duration spaceflight.

**IMPLICATIONS FOR FUTURE RESEARCH**

The critical path roadmap currently defines several important topics for research. At this time these seem to be a suitable summary of the needs for future research in the area of Sleep and Chronobiology, and indeed the presentations made broadly cover these critical areas.

The problem defined in the critical path is that of:

*Human performance failure due to disruption of circadian phase, amplitude, period, or entertainment, and/or human performance failure due to acute or chronic degradation of sleep quality or quantity.*

Research in the following areas will be necessary to solve these questions.

**Priority 1**

- What are the acute and long-term effects of exposure to the space environment on biological rhythmicity, on sleep architecture, quality and quantity, and their relationship to performance capability?
- Which countermeasure or combination of behavioral and physiological countermeasures will optimally mitigate specific performance problems associated with sleep loss and circadian disturbances during a Mars mission?

**Priority 2**

- What are the long-term effects of countermeasures employed to mitigate performance problems with sleep loss and circadian disturbances during a Mars mission?
- What are the best methods for monitoring the status of sleep and circadian functioning and for assessing the effects of sleep loss and circadian dysrhythmia that are also portable and non-intrusive in the spaceflight environment?
- What mathematical and experimental models best predict performance problems associated with sleep-wake and work history and circadian rhythm status, and also provide guidelines for successful countermeasure strategies?

**Lower Priority**

- What individual biological and behavioral characteristics will best predict successful adaptation to long-term space flight of sleep and circadian physiology and the neurobehavioral performance functions they regulate?